Nuclear Technology Development and Economics
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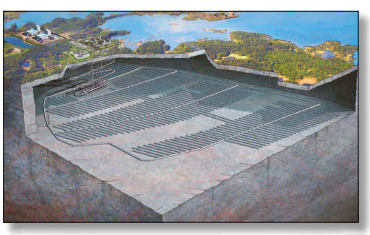
Strategies and Considerations for the Back End of the Fuel Cycle



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Nuclear Technology Development and Economics

Strategies and Considerations for the Back End of the Fuel Cycle

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– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

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Cover photos: Deep geological repository site in Oskarshamn, Sweden (SKB); Fuel reprocessing (Cogema).

Foreword

A wealth of technical information exists on nuclear fuel cycle options – combinations of nuclear fuel types, reactor types, used or spent nuclear fuel (SNF) treatments, and disposal schemes – and most, if not all, countries with active nuclear power programmes conduct some level of research and development on advanced nuclear fuel cycles. However, perhaps because of the number of options that exist, it is often difficult for policy makers to understand the nature and magnitude of the differences between the various options.

In this regard, this report explores the fuel cycle options and the differentiating characteristics of the options, and decision drivers related to both the development of the fuel cycle and the characteristics resulting from implementing the option. This publication has been prepared on the basis of information on the current situation of each country represented in the expert group including the current status and future plans for power reactors, reprocessing facilities, disposal facilities, and the status of research and development activities. This report is designed for policy makers to understand the differences among the fuel cycle options in a way that is concise, understandable, and based on the existing technologies, while keeping technical discussions to a minimum.

Acknowledgements

The report reflects the discussions that have taken place, over a two year and a half period since May 2017 and over four meetings of the Nuclear Energy Agency (NEA) Expert Group on Back-end Strategies (BEST), chaired by Mr William McCaughey. The list of members of the BEST Expert Group can be found at the end of this report. This report could not have been produced without their valuable contributions, or without the work of all the people who have collected and assembled the necessary information. The NEA also expresses its sincere gratitude to the members of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC), and the NEA Radioactive Waste Management Committee (RWMC) for their valuable comments.

Table of contents

List of annexes

List of figures

List of tables

Abbreviations and acronyms

ALLEGRO	Experimental fast reactor cooled with helium
BEST	Expert Group on Back-end Strategies (NEA)
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (France)
DGR	Deep geological repository
DOE	Department of Energy (United States)
EDF	Électricité de France
ERU	Enriched reprocessed uranium
HLW	High-level radioactive waste
IAEA	International Atomic Energy Agency
ISFSI	Independent spent fuel storage installation
ITER	International Thermonuclear Experimental Reactor
MCC	Mining and Chemical Combine (Russia)
MOTIE	Ministry of Trade, Industry and Energy (Korea)
MOX	Mixed oxide fuel (uranium and plutonium unless otherwise specified)
MTHM	Metric tonnes heavy metal
MYRRHA	Multi-Purpose hYbrid Research Reactor for High-tech Applications
NEA	Nuclear Energy Agency
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
ONDRAF/NIRAS	National Agency for Radioactive Waste and enriched Fissile Material (Belgium)
PHWR	Pressurised heavy-water reactors
PWR	Pressurised light-water reactors
RBMK	Reaktor Bolshoy Moshchnosti Kanalnyi (Russia)

R&D	Research and development
RRP	Rokkasho Reprocessing Plant (Japan)
PURAM	Public Limited Company for Radioactive Waste Management (Hungary)
RWMC	Radioactive Waste Management Committee (NEA)
SNF	Spent nuclear fuel
SYNATOM	Société belge des combustibles nucléaires (Belgium)
UNF	Used nuclear fuel

Executive summary

There is a vast amount of technical information associated to various nuclear fuel cycle options available as a result of research and experience conducted worldwide for decades. While it provides policymakers with useful insights, the myriad of options can confuse them and even give the perception that there is considerable technical disagreement as to whether any of the options result in a real improvement over the "once-through" uranium fuel cycle.

The Nuclear Energy Agency (NEA) established the Expert Group on Back-end Strategies (BEST) whose mission is to develop an understandable picture of the various nuclear fuel cycle options that are being considered by different countries, the reasons why each could be attractive in that particular case, and the aspects that are being or should be considered when making a decision to pursue or deploy a nuclear fuel cycle.

The expert group explored the fuel cycle options and the differentiating characteristics of each option. The current situation on fuel cycle options and the driving factors for the decision in each country represented in the expert group were discussed.

The fuel cycle options can be reduced in a first approach to three options based on physics and the processing of material through the fuel cycle: open-cycle, mono-recycle and multi-recycle. Open-cycle uses low enriched uranium in light-water reactors and will dispose of the spent nuclear fuel in a deep geological repository. Mono-recycle reprocesses the used nuclear fuel once to produce mixed oxide fuel (MOX) (depleted uranium and plutonium) and enriched reprocessed uranium fuel (ERU) that are again used in light-water reactors. High-level waste from reprocessing and the spent ERU and MOX fuel will be disposed of in a deep geological repository. Multi-recycle will introduce fast spectrum reactors to use fuel from multiple reprocessing cycles. As long as the cycle is active, only the high-level waste from reprocessing will be disposed of in a deep geological repository. Multi-recycle can be enhanced by the transmutation of the minor actinides to reduce the long-lived radionuclides requiring disposal.

Fourteen characteristics were considered to differentiate among the three fuel cycles. Four are related to developmental challenges: overcoming technical challenges, overcoming financial challenges, finding suitable geology and space, and gaining social acceptance. Five are related to opportunities following implementation: fostering economic development, preserving natural resources, managing waste characteristics, increasing energy independence and security of supply, and safeguarding the interests of future generations. A further five are related to risks following implementation: proliferation, security, worker safety, public and environmental safety, and sustainability.

Many challenges, opportunities, and risks are shared by all fuel cycle options to a similar degree. All require deep geological disposal and none are currently operating anywhere in the world. All of the fuel cycle options share other developmental challenges such as financial challenges and social acceptance. They also share a number of implementation risks such as proliferation, security, worker safety, public and environmental risk. The extent of these developmental challenges and implementation risks are not so different among the fuel cycle options to make them discriminators when comparing different options.

However, some challenges, opportunities, and risks are significantly different among the fuel cycle options. The amount of natural uranium required at the front end of the fuel cycle is less for mono-recycle and significantly less for multi-recycle when compared to open-cycle. The characteristics of the material that requires disposal is also significantly different among the fuel cycle options. For the material requiring deep geological disposal, the volume, heat load, and radiotoxicity is significantly less for multi-recycle than the open-cycle or mono-recycle. Technical challenges are much greater for multi-recycle but so too are the potential economic benefits.

In addition to the differentiating characteristics, additional decision drivers were considered: requirements for developing a national back-end strategy, the consequences of extended storage of spent nuclear fuel, country characteristics regarding the size of the nuclear power programme and the direction in which the programme is headed, and the potential benefits of shared infrastructure and international co-operation.

The expert group found that all countries need to be actively implementing a strategy for the back end of the fuel cycle. Prolonged delays in making decisions and in implementing decisions that have been made have increased costs and the probability of failure. In addition, the delay further transfers the burden onto future generations and ultimately harms the prospect for countries to reap future benefits of nuclear power. There is no one size that fits all that would drive all countries to a common fuel cycle or back-end strategy. Up to this point countries have made their decisions based on their history of nuclear power development and the priorities they place on the different characteristics of the fuel cycle options as well as their view on the long-term use of nuclear power. Energy policy may also evolve with time leading to change from one strategy to another.

All countries need to invest in knowledge management. The period of time required to implement any fuel cycle option through the final disposal of waste is extremely long. There are multiple technology options, some with high technology readiness levels available for deployment today and others with low technology readiness levels that will require additional research and development before they can be used. Without investing in knowledge management, countries risk losing future options due to a deteriorating research and development (R&D) infrastructure or the loss of technological options through attrition in the ranks of the technical staff needed to operate the technology.

Technology development through international collaboration should be accelerated in multi-recycle and enhanced recycle efforts. Accelerating technology development through international collaboration in multi-recycle and enhanced recycle efforts can lead to great improvements in many aspects of the back end of the fuel cycle. The open-cycle and mono-recycle are established technologies. Multi-recycle and enhanced multi-recycle require further technology development through research, development, and demonstration. These options may offer great improvements in preserving natural resources, waste characteristics, and energy independence. The Generation IV International Forum (GIF) is one such international collaboration that is working to deploy fast reactors that would facilitate multi-recycle and enhanced multi-recycle options.

International collaboration should be accelerated in facilitating shared infrastructure in used or spent nuclear fuel management. A small number of countries have large and ongoing nuclear power programmes and the infrastructure as well as technical expertise to develop their own back-end strategies. Economies of scale are in their favour. Many more countries with smaller programmes are faced with much costlier solutions relative to the size of their existing programmes. Sharing infrastructure related to nuclear fuel, in particular reprocessing facilities and deep geological disposal facilities could greatly benefit those countries.

Chapter 1. **Introduction**

There are various nuclear fuel cycle options being applied or proposed today. Each country has its own view of the attractiveness of different fuel cycle options that is influenced by real concerns (e.g. nuclear waste disposal, safety), perception of the general public (e.g. concerns about risks and the environment), potential options for disposal of spent nuclear fuel (e.g. size and type of suitable geological formations), the existence of indigenous technology (e.g. current or past fast reactor development programmes), existing and required infrastructure, cost, and other considerations.

In 2013, the Nuclear Energy Agency (NEA) published *The Economics of the Back End of the Nuclear Fuel Cycle* (NEA, 2013) providing a review of the relative costs of various nuclear fuel cycle options, which found that the costs associated with advanced fuel cycles were only slightly higher than the once-through cycle and within the uncertainty bands when the front-end uranium savings are taken into account. As noted above, while costs are certainly an important consideration, they are clearly not the only consideration weighing into fuel cycle decisions. The NEA Nuclear Science Committee (NSC) has performed technical studies on different technology options, their development status, schemes for phasing in such technology, optimal combinations of technologies, and the like (NEA, 2018). This study seeks to build upon and harmonise these efforts with the considerations of a policy maker contemplating the deployment of an advanced fuel cycle.

It would be very useful for policy makers to have a clear and comprehensive picture of the various nuclear fuel cycle options that are being considered by different countries. Further, policy makers need to know the reasons why each is attractive in that particular case, and the aspects that are being or should be considered when making a decision to pursue or deploy an advanced nuclear fuel cycle.

Chapter 2 describes the fuel cycle options: open-cycle, mono-recycle, and multi-recycle. It then explores the differentiating characteristics of each option related to both the development of the fuel cycle and the characteristics resulting from implementing the particular option.

Chapter 3 describes the current situation in each country represented in the expert group. It includes the current status and future plans for power reactors, reprocessing facilities, disposal facilities, and the status of research and development activities.

Chapter 4 adds a discussion of decision drivers other than the characteristics noted in Chapter 2. These include multinational directives such as the European Union directive on nuclear waste management and how roles and responsibilities for nuclear waste management are defined in each country.

Finally, Chapter 5 presents findings and recommendations that would be useful for policy makers to consider when deciding on the various fuel cycle options to pursue.

References

NEA (2013), *The Economics of the Back End of the Nuclear Fuel Cycle*, OECD Publishing, Paris.

NEA (2018), *State-of-the-Art Report on the Progress of Nuclear Fuel Cycle Chemistry*, OECD Publishing, Paris.

Chapter 2. Description of fuel cycle options and their characteristics

This chapter sets the stage for the rest of report. It first describes the options (Section 2.1) and then the characteristics (Section 2.2) that would factor into decision making on pursuing different fuel cycle options. The characteristics are related to the options and are independent of the circumstances of the countries that would be involved.

The discussion focuses on the main fuel cycle options and characteristics based on how they are typically implemented. There are many slight variations on these main options that can have minor impacts on their characteristics. For the purposes of readability only the most significant variations are discussed, typically in footnotes, for the benefit of those already familiar with these issues.

2.1. Description of the nuclear fuel cycle options

2.1.1. Background – What is a fuel cycle?

Uranium is unique in nature in that it has a fissile isotope,[1] a variation of the uranium atom that can be split in two fragments (fissioned) when it absorbs a neutron, resulting in two lighter elements (fission products), two or three surplus neutrons, and a lot of energy. This is the basis of nuclear power.

A nuclear fuel cycle covers the activities related to fuelling nuclear reactors and managing used nuclear fuels. The nuclear fuel cycle starts with the mining of uranium (and possibly thorium) and ends with the disposal of nuclear waste. It goes through the steps of mining and milling, conversion, enrichment and fuel fabrication, which are called the "front end" of the fuel cycle. After fuel has been irradiated[2] for four to five years in a reactor to produce electricity, the used or spent nuclear fuel[3] may go through a further series of steps including interim storage, transportation and/or reprocessing before spent nuclear fuel or high-level waste[4] are disposed. These steps are known as the "back end" of the fuel cycle.

The primary fuel cycle used today is described below:

Uranium in its natural form is composed of 99.3% of the "fertile" isotope, uranium-238 and 0.7% of the "fissile" isotope, uranium-235. The uranium is processed to produce an "enriched uranium" product that is ~95% fertile and ~5% fissile and a waste stream of "depleted uranium" that is almost 100% fertile. The enriched uranium is made into ceramic pellets that are placed inside metal "cladding" tubes. The tubes are arranged in a square lattice that makes up a fuel assembly. These fuel assemblies are placed in the core of the reactor.

1. A fissile isotope is an isotope that can undergo nuclear fission under the effect by absorption of a neutron any energy. The only natural fissile isotope is uranium-235. A fertile isotope is an isotope that is transformed in a fissile isotope through neutron capture (i.e. two neutrons are needed to induce a fission).
2. In this document, "burning" or "irradiation" refers to subjecting nuclear fuel to neutron radiation within a reactor, resulting in controlled consumption of fissile isotopes in the fuel.
3. Fuel is considered "used" if it will be recycled and "spent" if it will be disposed as waste.
4. High-level waste results from recycling used fuel with the reusable materials separated from the waste materials. These waste materials are initially highly radioactive and become less radioactive over time.

The fuel is "burned" (fissioned) in reactors until most of the fissile atoms have split and the fissile content drops too low to continue. At this point, the fuel is "spent" nuclear fuel (SNF) or "used" nuclear fuel (UNF),[5] and composed of ~93% fertile uranium, ~1% fissile uranium, ~5% fission products, ~1% plutonium, and ~0.1% minor actinides.[6] Plutonium and the minor actinides (neptunium, americium, and curium) are elements heavier than uranium that are created in a reactor when fertile uranium captures neutrons.

Most of the fuel content is chemically poisonous and radioactive. Being radioactive means that an isotope is unstable and will emit one or more small particles to become stable (a process called radioactive decay).

These small particles can affect cells and if a person is exposed to a lot of them, the person may become ill. A second effect of the radioactive decay is heat generation: the emitted particles will interact with matter and generate heat. For these reasons, UNF or SNF must be managed with care.[7]

UNF or SNF is discharged from reactors and cooled in deep pools of water for several years. These pools serve two functions: protecting the workers from the radiation emitted and evacuating the heat generated by the spent fuel.

After the fuel has cooled, there are several options of what comes next on the back end. The important factors to understand are:

- Almost all of the fuel content is radioactive and decays at different rates. In the relatively short term (a few hundred years or less), most of the fission products (named short-lived fission products) decay and are no longer radioactive. The remaining fission products (long-lived fission products), and some isotopes of uranium, plutonium, and minor actinides remain radioactive for a very long time (many thousands of years).
- Uranium from irradiated fuel has as much, or even more residual fissile content than natural uranium; plutonium is mostly fissile. Thus, UNF from current reactors is a potential source of fissile material.
- In a reactor, some fertile material will capture neutrons and change into fissile material. In today's water-cooled reactors, the amount of new fissile material created is less than the amount consumed. However, different reactor concepts can produce more fissile material than they consume. These are called breeder reactors.
- The design and extent of a final disposal option is driven by the nature of the material for disposal. Geometry, size (mass and volume) but also decay heat are factors in the choice of size, surface and volume (and cost) of such a repository.

Thorium is the only other abundant element[8] in nature that has a fertile isotope. It is also about three times more abundant than uranium. For this reason, during the early development of nuclear energy, thorium was considered a fuel that could potentially supplement or even replace natural uranium. At the time, uranium was thought to be of limited availability. Natural thorium is 100% composed of the fertile isotope thorium-232. A sustainable thorium fuel cycle must be started with fissile-enriched uranium and must then breed more fissile material from the fertile thorium. Once it was found that uranium was relatively abundant, interest in this

5. The term "spent nuclear fuel (SNF)" is used only in fuel cycle options in which spent fuels are defined as waste. Otherwise, the term "used nuclear fuel (UNF)" is used. For example, in mono-recycle, irradiated uranium oxide fuel will be a UNF while irradiated MOX recycled one time will be an SNF.
6. The total does not add to 100% due to rounding.
7. The primary health risk is from inhalation or ingestion of isotopes that decay quickly, as they have a greater chance of decaying while in the human body. Isotopes with very long decay times primarily contribute to health risk indirectly when they decay into other radioactive isotopes with much shorter decay times.
8. Protactinium is the naturally occurring (but extremely rare) element between thorium and uranium which can also fission.

more complicated fuel cycle waned, although proponents still see potential for its development. The important factor to understand is that a thorium fuel cycle requires starting with a combination of uranium and thorium, then recycling the UNF. The technology for a thorium fuel recycle has not yet been developed to an industrial scale.

2.1.2. *The main fuel cycle options*

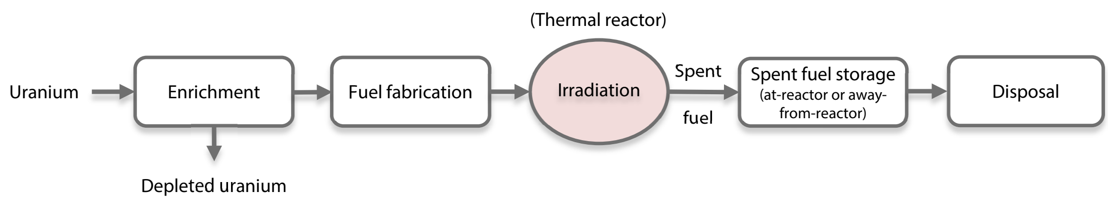
The basis for the main types of fuel cycles is described above. This includes whether fuel is directly disposed as waste, recycled once to use the small amount of remaining fissile material, or recycled multiple times (continuously) in breeder reactors to convert and use the remaining large amount of fertile material. Fissioning the remaining fissile and fertile materials produces more energy from the mined uranium (and thorium, if used) while removing the source of much of the long-term radioactivity in the nuclear waste.

2.1.3. *Open-cycle*

The open-cycle, as described above in the background Section 2.1.1, is the fuel cycle currently considered as the reference option in most nuclear countries. At its heart is a thermal neutron reactor,[9] typically cooled by ordinary (or light) water.

There are two variations: heavy-water reactors and gas-cooled reactors. Both of these can operate with natural (unenriched) uranium, while light-water reactors and some of the gas-cooled reactors require uranium enrichment. At the back end, the cooled SNF assemblies are safely stored pending their disposal in a deep geological repository.[10] The storage may take place at the reactor site or away from the reactor. Except for the packaging and conditioning they will need to comply with transport and disposal requirements, the SNF will not receive any particular chemical treatment. The open-cycle is shown in Figure 1.

Figure 1. **Open-cycle**



2.1.4. *Mono-recycle*

This is a two-stage fuel cycle. The first stage is as explained above up to the point of how the cooled UNF is managed.

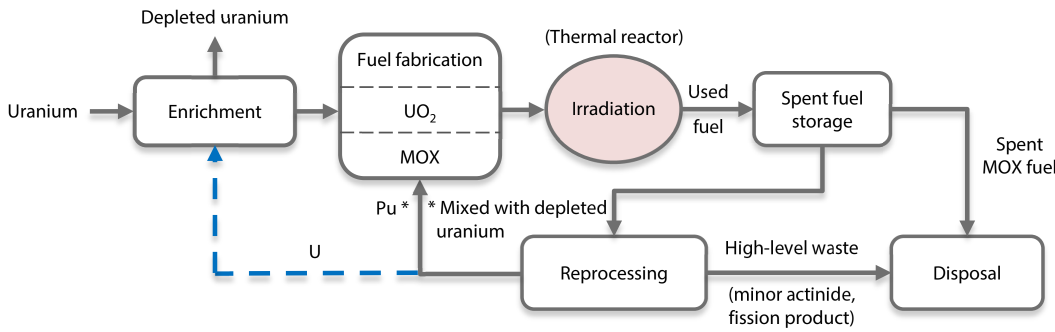
The cooled fuel from the first stage is chemically separated (reprocessed), with the uranium and plutonium recovered for reuse in the second stage and the minor actinides and fission products ("high-level waste" or HLW) is placed into solid, stable waste forms (usually vitrified into glass) and packaged in stainless steel containers. The HLW is stored pending disposal in a deep geological repository. The volume of this waste is smaller than the volume of SNF of the open-cycle. The fuel hardware (cladding, etc.) is also packaged for disposal as medium level

9. A thermal reactor is a nuclear reactor in which nuclear fissions are caused by neutrons that are slowed down by a moderator. On the other hand, fast reactor, as shown in Figure 3, is a nuclear reactor in which nuclear fissions are caused by fast neutrons because little or no moderator is used.

10. A deep geological repository is a radioactive waste repository excavated deep within a stable geological environment. It is designed to safely contain and isolate spent fuel or high-level waste over the long term without future need for maintenance or even oversight.

waste that can usually be disposed safely in properly engineered shallow landfills or intermediate-level waste repositories depending on national regulations. The mono-recycle fuel cycle is shown in Figure 2.

Figure 2. **Mono-recycle**



All of the plutonium mixed with depleted uranium is used to make mixed oxide fuel (MOX) that is placed back into the reactors. It takes about eight UNF assemblies to recover enough plutonium for one MOX fuel assembly. Recycle of the plutonium allows the fissile content in the plutonium (about 60%) to be used in fuel. When this MOX fuel is spent, it is placed in the SNF pool for cooling, followed eventually by geological disposal only in case multi-recycle scheme is not implemented.[11] This is why this fuel cycle is called mono-recycle, as the fuel is only recycled once. There is lower fissile content left in the fuel after this single recycle (about 50%).

The majority of the remaining uranium from the first stage can be re-enriched to make additional fuel. The recovered uranium[12] is only mildly radioactive and can be kept as a future resource or disposed in a manner similar to low-level waste.

This fuel cycle requires only about 75% of the natural uranium needed for the open-cycle due to the reuse of the fissile isotopes.

2.1.5. *Multi-recycle*

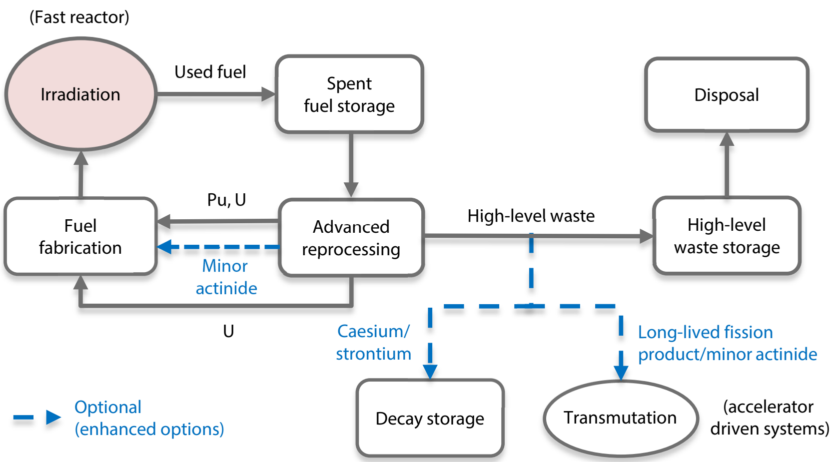
Multi-recycle has not been developed at industrial scale and is the subject of research and development (R&D) in many countries and in multinational collaborations. As the name implies, this fuel cycle is similar to the mono-recycle fuel cycle described above, except that the fuel is recycled multiple times, each time with the uranium and plutonium recovered and the minor actinides and fission products disposed of.

In general, to have enough fissile material for a multi-recycle, a different type of reactor is used for the second stage, a fast reactor.[13] This type of reactor uses neutrons with higher energies. This results in more plutonium being made from the fertile uranium. The result is roughly the same amount of plutonium in the UNF as was in the fresh fuel (for a "break even" fast reactor) or even more plutonium (for a "breeder" fast reactor). The uranium and plutonium

11. Mono-recycle is often proposed as a first step towards enabling to move to multi-recycle in the future.
12. Recovered depleted uranium is slightly different from the depleted uranium obtained from the enrichment of natural uranium because of the presence of some isotopes of uranium produced during irradiation.
13. Multi-recycle is also possible in thermal reactors, but usually requires an external source of fissile material. For example, the Russian REMIX fuel is the non-separated mixture of U and Pu from light-water reactor SNF reprocessing, augmented with enriched uranium; MIX (mixed enriched UO_2/PuO_2) or CORAIL (uranium oxide and mixed oxide rods) fuel developed in France also use enriched uranium. This approach is close to mono-recycle with respect to uranium needs.

can be recycled continuously, as long as additional fertile uranium is added each cycle to make up for the loss of fissile material. The extra uranium recovered from the first stage can be used for this, or depleted uranium can be used. In addition, the minor actinides and fission products produced during each cycle must be separated and disposed of as waste. The back end of the first stage and the second stage of this fuel cycle is shown in Figure 3.

Figure 3. **Multi-recycle**



Because all fissile uranium and plutonium produced from fertile uranium can be consumed in this cycle, the amount of natural uranium needed to produce the same amount of energy can be decreased significantly. Fast reactors can use plutonium they produce or plutonium produced by water reactors including light-water reactor (LWR) MOX fuel indefinitely, thus getting the most out of its energy potential while avoiding the long-term disposal of SNF containing uranium and plutonium.

Enhanced recycle can also transmute the minor actinides (particularly neptunium, americium and curium) to further reduce the amount of HLW, as well as how long it will remain hazardous. These options are under development and require additional technologies to separate the UNF into additional streams, to fabricate the fuel, and to transmute isotopes. Fuels containing minor actinides are highly radioactive, which makes the industrial assets much more complex; the fuel must be fabricated remotely in special shielded "hot cells". To achieve sufficient transmutation of minor actinides and long-lived fission products, accelerator-driven systems may be used in addition to fast reactors.[14] In recent years, interest has grown in the possibility of separating (or partitioning) the long-lived radioactive waste from UNF and transmuting it into shorter-lived radionuclides. This partitioning and transmuting technology can reduce the amount of radioactive waste and the associated decay heat and long-term radiotoxicity, and as the result, the management and eventual disposal of this waste is easier (NEA 2011). However, this further step adds additional expense.

In enhanced recycle, high heat emitters such as caesium and strontium can be separated and stored in dedicated storage containers for several hundred years until the heat from the waste reduces to be negligible[15] as shown in Figure 3. This option is to reduce significantly the foot print of the final waste repository and so it may be considered as an option for countries without large and stable rock systems. Since the minor actinides make up such a small amount of the total SNF, these enhanced options do not significantly change the amount of uranium needed from the (Pu) multi-recycle fuel cycle.

14. The approach using molten salt reactors is also under development in Russia.

15. This is known as "decay storage".

2.2. Differentiating characteristics

This section compares each of the fuel cycle options against 14 characteristics that are either characteristics related to the *development* of the fuel cycle (e.g. financial challenge to implement) or characteristics related to the outcome of implementing the fuel cycle option (e.g. economic development opportunities). Some outcomes relate to *opportunities* presented when the fuel cycle option is implemented. Other outcomes relate to *risks* related to the fuel cycle option once it is implemented.

Table 1 lists the differentiating characteristics and provides a brief summary of the differences between fuel cycles. Following the table are definitions of each characteristic and a lengthier summary of the differences between the fuel cycles.

Table 1. **Differentiating characteristics for nuclear fuel cycles**

Challenges in the development of fuel cycle options	
C.1. Overcoming technical challenges Technical challenges require specific scientific and engineering expertise to address, and may also require additional R&D.	Greater technical challenges are present in the mono-recycle and multi-recycle options with the enhanced multi-recycle option posing the greatest technical challenge.
C.2. Overcoming financial challenges Spent or used nuclear fuel management is a major financial challenge requiring long-term strategic planning.	Different options have different requirement profiles but also different risks and uncertainties evolution with time: the open-cycle has lower short-term costs but uncertainties about waste hazards increase with time, mono- or multi-recycle having higher short or mid-term costs but the characteristics of the waste limit the long-term hazard, thus reducing future uncertainties.
C.3. Finding suitable geology and space Suitable geology and space are physical characteristics of the land below ground that are relevant to the potential siting and safe operation of any fuel cycle option.	A suitable geology and space is a very important characteristic when considering the open-cycle. The space required is lower when mono or multi-recycle are considered.
C.4. Gaining social acceptance Without social acceptance, certain back-end pathways may be more difficult and expensive, or even impossible, to achieve.	Social acceptance is a common issue for all options but there exist differences that depend on specific situations in certain countries.
Opportunities when a fuel cycle option is implemented	
O.1 Fostering economic development The implementation of fuel cycle options leads to new socio-economic opportunities.	In general, recycle options have more opportunity to provide indirect and direct economic benefits compared to the open-cycle.
O.2. Preserving natural resources Depending on the strategy implemented for the back end of the fuel cycle, the requirement for uranium resources varies significantly.	Compared to the open-cycle, mono-recycle reduces natural uranium needs up to 25%, while multi-recycle dramatically reduces natural uranium needs by 99%.
O.3. Managing waste characteristics (volume, heat, radiotoxicity) The choice of a fuel cycle option will have a large impact on the characteristics of the final waste.	Reprocessing and resulting nuclear material burning in reactors reduces the decay heat, amount of high-level waste, and ingestion radiotoxicity.
O.4. Increasing energy independence and security of supply Energy independence depends on the local vs regional availability of uranium resources, and facilities for its conversion, enrichment, fuel fabrication, reprocessing and recycling.	Energy independence and security of supply is low for an open-cycle. If facilities exist nationally, multi-recycle is totally self-sufficient. (Only very small amounts of fertile material are needed.)
O.5. Safeguarding the interests of future generations Considering the long time required for high-level radioactive waste to decay, there is an ethical aspect of leaving this problem to future generations. Using natural uranium is reducing natural resources for future generation.	The interests of future generations are inherent in all of the differentiating characteristics. Today's decisions determine the opportunities, risks and challenges of future generations.

Table 2. **Differentiating characteristics for nuclear fuel cycles** *(cont'd)*

Risks when a fuel cycle option is implemented	
R.1. Proliferation Allowing the diversion or undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons.	The primary proliferation risks are from enrichment and reprocessing and depend on whether these operations occur domestically or are services provided by other countries.
R.2. Security The protection or detection of nuclear material to avoid its diversion or theft by non-state actors, such as sub-national or other external groups.	In general, the importance of security depends more on the location of the facilities than on many other factors given that the threat is from an external party.
R.3. Worker safety In addition to traditional industrial risks, nuclear installations have to take into account protection against exposure to ionising radiation.	In mono- and multi-recycle, uranium mining is reduced* as well as the associated exposure and risks. However, the differences between open-cycle and recycling options regarding worker exposure are very small; radiological impact to workers is not a key factor favouring one or the other option.
R.4. Public and environmental safety The greatest public risk is from trucks transporting material. The primary environment impact is land disturbance caused by uranium mining.	Generally, as recycling increases, public and environmental risks decline because less bulk material is mined and shipped. However, the land disturbance can be minimised with proper remediation.
R.5. Sustainability Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987)**	All of the fuel cycle options can be generally consistent with the fundamental sustainable development goal. Sustainable development depends on the long-term availability and environmentally sound production of fuel and UNF or SNF management. In this aspect, the open-cycle is relatively less sustainable as it uses more natural resources and produces more long-lived HLW than other fuel cycle options.

* Collective dose to workers from fuel cycle components is the largest in mining and milling stage except for nuclear power plant operation (NEA, 2001).

** Brundtland, 1987.

2.2.1. *Challenges to development of the fuel cycle options*

C.1. Technical challenge

There are varying degrees of technical challenges present and technical expertise needed depending upon the back-end option being considered. A variety of technologies and concepts to manage SNF and HLW has been developed, but not all concepts are currently being industrially implemented.

Open-cycle – Direct geological disposal does not represent a major technical challenge. The knowledge required to build a repository and encapsulate and emplace the waste, and to close and monitor the repository are established or could be developed from present knowledge. The world's first geological repository for SNF disposal is now under construction in Finland. Types of expertise needed include geologists to study and model the behaviour of the repository, health physicists to address issues related to the radioactive nature of the SNF and HLW, and engineers to design the packages and the system of barriers to be used. Expertise in modelling is needed to better understand the physical and chemical processes involved and their risks.

Mono-recycle – This option requires geological disposal and has to address the same technical challenges as the open-cycle. This option also requires facilities for reprocessing UNF and MOX fuel fabrication which are or have been commercially operated in some countries. Commercial reprocessing plants use well-proven processes to separate uranium and plutonium. Significant technical expertise is needed to support this option in the form of chemists and chemical engineers to focus on processes and process engineering and design, materials experts, health physicists, as well as engineers to design, construct and operate a plant.

Multi-recycle – This option has the same reprocessing and MOX fuel fabrication challenges as mono-recycle. It also requires the development and operation of fast reactors. Geological disposal is still required, but only for HLW that remains hazardous for less time than SNF. The enhanced recycle option further reduces waste hazards, but requires additional chemical separation processes and remote fuel fabrication, neither of which have been implemented before at industrial scale. New separation techniques such as advanced head-end processes, co-processing solvent extractions, and pyroprocessing are also being investigated in different member states and their technological maturities were described in a recent NEA report (NEA, 2018).

- Summary

There is a wide range of technical challenges across back-end options along with varying levels of expertise needed to address these challenges. In general, the necessary technology for geological disposal is available and can be deployed when public and political conditions are favourable (NEA, 2018). However, there is relatively little industrial level experience in the application of some of these technologies and therefore demonstration and testing will continue and further refinements will be made. Considering that all fuel cycle options need a deep geological final repository, greater technical challenges are present in the partial and full recycle option, with the enhanced full recycle option posing the greatest level of technical challenge.

C.2. Financial challenges

UNF or SNF management is a major financial challenge requiring long-term strategic planning. Today, most countries have implemented funding mechanisms to accumulate money for this purpose. All of the major facilities enjoy economies of scale, where large capacity facilities are less expensive on a per-unit basis if demand is sufficient for full utilisation. For this reason, smaller nuclear programmes may want to share facilities or pay larger programmes for recycling services.

Open-cycle – Construction and operation of the deep geological repository (DGR) is the major back-end cost for this option. Since these costs typically occur decades after energy production, upfront payments into a disposal fund can be modest as long as the funds are invested properly for compounded growth. However, if unforeseen delays in putting the DGR in operation should occur, SNF may remain in storage at reactor sites for much longer periods, even after the reactors are shut down and required fuel handling facilities have been dismantled. While this presents no safety concerns, it could add cost and require new facilities to support fuel packaging/ repackaging during storage and during preparation for disposal once the repository becomes operational and begins accepting SNF.

Mono-recycle – This option adds the need to construct and operate reprocessing and MOX fuel fabrication facilities. Because these costs are incurred concurrent with energy production, large upfront payments are necessary. An alternative to these major construction investments is to contract for services offered by owners of existing recycle capacities.

DGR costs may be reduced modestly due to the removal of much of the uranium during the mono-recycle, which can instead be disposed as low-level waste, but waste hazard and longevity of the combined HLW and SNF are similar to a once-through fuel cycle.

Multi-recycle – This requires investments in recycling facilities and higher reactor costs for fast reactors instead of thermal reactors. Both are upfront costs. Significant cost savings for the DGR may be realised because decay heat, volume of HLW, and inhalation radiotoxicity will be significantly reduced.

Multi-recycle can be implemented in stages starting from a mono-recycle option, and organising a smooth transition to a symbiotic light-water reactor and fast reactor fleet or full fast reactor fleet depending on the natural uranium resources and the evolution of the nuclear installed capacity or by developing shared facilities to profit from economies of scale.

- Summary

Regardless of the selected cycle option, financial requirements have to cover all operations for the complete management of UNF or SNF up to the final disposal of radioactive waste, and even beyond the closure of the DGR. Financial requirements to cover UNF or SNF management have to consider the holistic approach, encompassing short-term stages but also the very long-term duration of the overall system or programme. Different options have different requirement profiles but also different risks and uncertainties that evolve over time: the open-cycle has lower short-term costs but uncertainties about waste hazards increase with time, close cycle options having higher short- or mid-term costs but the characteristics of the waste limit the long-term hazard, thus reducing future uncertainties.

Economies of scale could be an important factor for smaller countries and newcomers. Sharing back-end infrastructures that require significant investment, either for a large fleet of reactors within one country and/or among different countries, would be a way to significantly reduce the financial burden.

C.3. Suitable geology and space

The longer-lived radioactive hazards whether in SNF or HLW must be contained and isolated from humans and the environment for a very long time. Disposal of this waste located deep underground in suitable geological formations that can isolate the waste from the environment until the radioactivity level is low enough is recognised as the reference management system. Suitable geology of sufficient size to host a DGR is a requirement of any fuel cycle option. Understanding how a DGR site will react to both its excavation and the decay heat of the emplaced waste is extremely important (NEA, 2017a, 2015a, 2012). The size of the repository and the time frame for waste isolation differs depending upon the option under consideration, with short- (for decades) to medium-term (for hundreds of years) decay heat driving repository size and long-term (millennium scale) radiotoxicity driving the time required for the radiotoxicity of waste in the repository to decay to the level of natural uranium.

Open-cycle – This option requires the most repository space per unit of electricity generated, generates the most decay heat, and requires the longest period to decrease their radiotoxicity to the level below natural uranium among the three options.

Mono-recycle – This option significantly reduces the amount of uranium going to the repository compared to the open-cycle, but only slightly reduces decay heat. Short-term hazards are mostly unchanged, while long-term radiotoxicity are reduced due to the removal of ~85-90% of the uranium and consumption of a small portion of the plutonium.

Multi-recycle – This option removes almost all of uranium and plutonium going to the repository compared to the open-cycle. The enhanced version also eliminates most of the medium-term decay heat. Short-term decay heat is slightly reduced.

- Summary

Suitable geology and space is the most important in the open-cycle which requires the most repository space among three options. The importance is reduced some with either partial or full recycle, although these options still require a deep geological repository for HLW. The space required and the duration of the geological isolation is reduced the most for multi-recycle.

C.4. Social acceptance

Social acceptance is a key consideration when developing any nuclear power system, including the back-end strategy. Social rejection is usually based on fear and uncertainty, while acceptance generally increases when people are better informed and invited to be involved. Stakeholder involvement in decision making provides the opportunity to increase public awareness, transparency and understanding and, ultimately, acceptance or support of decisions in the nuclear energy arena (NEA, 2017b, 2015b, 2002).

The public acceptance of the benefits of nuclear energy does not inherently include the acceptance of a deep geological repository as a back-end option. In general, accepting a deep geological repository is a challenge in itself for most societies. Gaining social acceptance is one of the most significant challenges to siting and operating a deep geological repository. The challenges for siting a consolidated interim storage facility are similar because of the de facto concern that the interim site could become the permanent one. Issues related to safety, non-proliferation, and environmental impact will be paramount. Understanding the contributions of engineered barriers (including waste packages) versus geological criteria will be important. Social acceptance could be enhanced by ensuring that local communities have a role in deliberating choices for either interim storage or direct disposal. Issues related to social acceptance of transportation of the SNF to these facilities must also be considered.

Open-cycle – The primary differentiating factors for the open-cycle are the large amounts of SNF that initially have no disposal until a DGR is developed and the uncertainty associated with long-term isolation of the SNF.

Mono-recycle – This option includes a near-term disposal path for the initial SNF, but not for the HLW and spent MOX fuel until the DGR is developed. Reprocessing may be perceived as a new source of hazard, including new types of waste, but also as a significant generator of well-paid jobs. Detractors will also raise proliferation concerns.

Multi-recycle – Social acceptance of the full recycling option will be tied to public understanding of the benefits as well as the perceived and real risks of the advanced technologies. Many of the concerns are the same as for mono-recycle. The differences include uncertainty on the development and deployment of fast reactors countered by a much stronger case for the associated recycling benefits and reduction in waste.

- Summary

Social acceptance is more of a common issue for all options (i.e. social acceptance of nuclear energy as a whole) and few significant differences exist among the different options. Social acceptance is generally higher when people are well informed and there is less uncertainty. Uncertainty can be reduced by considering technologies already in use and by building new facilities at sites of existing nuclear energy development. New technologies and new sites may require greater stakeholder engagement efforts to address the real and perceived risks of such options. Sustainability interests may support social acceptance of recycle options.

*2.2.2. **Opportunities when a fuel cycle option is implemented***

O.1 Economic development

Nuclear power plants create more jobs and for a longer term compared to other low-carbon energy sources (Deloitte, 2019). Likewise, the implementation of fuel cycle options leads to new socio-economic opportunities. The development of fuel cycle facilities creates new jobs which are well paid and require highly trained engineers, physicists, chemists, IT specialists, administrative and security staff. Jobs in the nuclear industry are secure and long-term, offering excellent career opportunities. In addition, there are direct and secondary effects in the local economy. The direct effects include tax and direct expenditures for goods, services and labour. The secondary effects include subsequent spending attributable to the presence of the plant and its employees as expenditures through the local economy, as well as secondary facilities such as education facilities to provide worker training.

Open-cycle – The main facilities at the back end include interim storage, transportation and disposal of SNF. Compared to other fuel cycle options, economic activities and expenditures induced from these facilities will be relatively small and the effects on economic development in local communities will be less significant.

Mono-recycle – In mono-recycle, reprocessing and MOX fuel fabrication plants are added and they create additional jobs and opportunity to provide more indirect benefits compared to open-cycle. For instance, in France the reprocessing plant in La Hague accounts for around 5 000 direct jobs and the Melox MOX fuel fabrication plant directly employs 800 people. Detailed economic impacts of the La Hague facility are described in Annex A.

Multi-recycle – The multi-recycle option requires additional back-end facilities and more activity to treat UNF and recover and package radioactive waste. More complicated technology, including fast reactors, requires more experienced experts and could provide more jobs, especially high-paying jobs, in the local community.

- Summary

In general, recycle options with different processing steps including reprocessing and fuel fabrication have more opportunity to provide direct and indirect benefits for economic development compared to the open-cycle.

O.2. Preserving natural resources

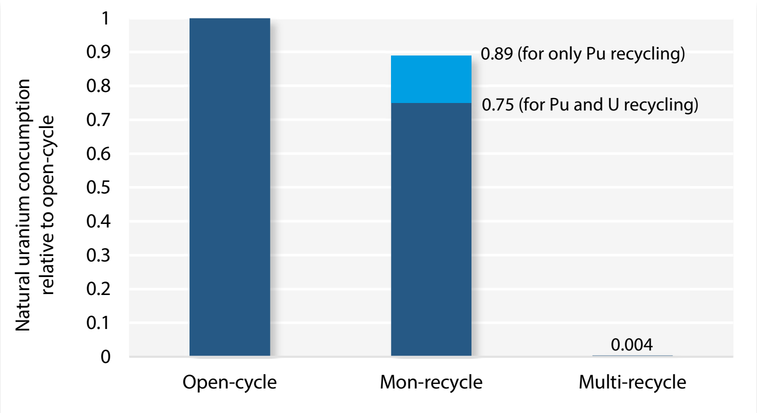
In 2017, the total amount of identified resources of uranium was 8 million tonnes of uranium metal (tU) and the total amount of undiscovered economically recoverable resources was estimated at an additional 7.5 million tU (NEA, 2018). Depending on the strategy implemented for the back end of the fuel cycle, the amount of natural uranium resource necessary for supplying a certain amount of energy varies significantly sustainability of these resources varies significantly.

Open-cycle – The main supply for uranium based fuel fabrication is natural uranium mining. On 1 January 2017, a total of 449 commercial nuclear reactors were connected to the grid in 30 countries and 64 reactors were under construction. Global requirements have increased from 57 980 tU in 2015 to 62 825 tU as of 1 January 2017 (NEA, 2018). Assuming an open-cycle with the current number of reactors, the total identified resources of uranium will run out after about 130 years. Reducing the amount of fissile material left in depleted uranium could extend stocks by about 10%. Improvements in mining technology also continue to extend this time frame by reducing the amount of energy required to extract uranium, making lower quality or deeper ore bodies economical to mine.

Mono-recycle – Reprocessing UNF contributes to preserving natural resources as it allows the reuse of two fissionable materials accounting for about 2% of the UNF metal mass. First, the plutonium created in reactors can be recycled to produce MOX fuel which can be loaded in reactors licensed to use this type of fuel. Second, the uranium recovered through reprocessing of UNF, known as reprocessed uranium, can be re-enriched and recycled to produce additional fuel which can be loaded in reactors licensed to use this type of fuel. If the recycle of the reprocessed uranium is included, mono-recycle can result in up to 25% in natural uranium savings (Zohuri and McDaniel, 2018).

Multi-recycle – The full recycle option in fast reactors uses not just the limited amount of UNF that is fissile material, but also the more than 90% that is fertile material. In addition, it can use the much larger quantities of depleted uranium that currently are considered waste.[16] This multi-recycle strategy can be considered sustainable as the amount of fertile material needed to support current nuclear electricity generation rates would only be a few hundred tU per year and current stocks of depleted uranium alone would last for several thousand years without any additional mining. Figure 4 shows the natural uranium consumption relative to open-cycle.

Figure 4. **Natural uranium consumption relative to open-cycle**



Source: NEA, 2006; Zohuri and McDaniel, 2018.

16. Roughly 8 to 10 tU of depleted uranium are generated for each tU of enriched uranium produced.

- Summary

In an open-cycle strategy, the reduction of depleted uranium tails assay[17] or the re-enrichment of depleted uranium tails can allow around 10% natural uranium demand reduction. Reprocessing UNF in the mono-recycle scenario allows fuel fabrication with either plutonium or reprocessed uranium saving up to about 25% natural uranium. In a multi-recycle scenario, on top of an initial inventory of fissile material, stocks of depleted uranium provide sufficient quantities of fertile materials to fuel fast reactors almost indefinitely, saving 100% of natural uranium resources.

O.3. Waste characteristics (volume, heat, radiotoxicity)

UNF or SNF poses one of the greatest challenges in nuclear energy production. When fresh uranium oxide fuel is irradiated, radioactive elements are created that are typically grouped in three different categories: the uranium/plutonium family, the fission products and the minor actinides (neptunium, americium, curium). The choice of a fuel cycle option will have a large impact on the characteristics of the final waste but in all cases, final disposal for this waste is needed.

Differences in heat load and waste volume may have a major impact on the size of a repository. Decay heat usually drives the design, with the maximum allowable disposal density determined by thermal limitations. A low thermal output of HLW allows the footprint of a repository to be reduced. Decay heat can be reduced by 1) storing the SNF or HLW longer before emplacement in the repository (decay storage) 2) separating the relatively short-lived[18] high decay heat producing fission products caesium-137 and strontium-90 from the HLW for separate decay storage, and/or 3) consuming the medium-lived[19] high heat producing isotopes plutonium-238 and americium-241. The volume of HLW to dispose of is another factor that can impact design if decay heat has been sufficiently reduced.

Open-cycle – SNF constitutes the waste for this fuel cycle option. In most concepts, disposal of the SNF occurs after several decades of cooling in wet or dry storage. The SNF is spaced as needed to prevent damage to the repository geology or backfill, for example, drying and cracking of a clay formation in case SNF is disposed of in clay repository.

Mono-recycle – During the single recycle pass, uranium and plutonium are recovered and recycled in MOX and enriched reprocessed uranium (ERU) fuel while the fission products and minor actinides are converted to a glass (vitrified) and placed in canisters. Fuel hardware (cladding, spacers grids, etc.) contaminated with radioactive material are compacted and also placed in canisters. The canisters, waste form and other engineered barriers work together with the geology to confine the waste for long periods to reduce any remaining radiotoxicity via final decay into stable, non-radioactive isotopes. The spent MOX or ERU fuels are cooled down in interim storage before being packaged and disposed. SNF will have greater ingestion radiotoxicity than HLW for a very long time.[20]

Multi-recycle – In multi-recycle, the uranium/plutonium family is recycled a large number of times until it is fully consumed in fast reactors. In this option, there is no SNF disposal as long as the fuel cycle is active, only vitrified waste containing fission products and minor actinides. Due to fast reactor fuel design, there is more compacted waste (continuing metallic structure) than for mono-recycle. This option greatly reduces the volume of final waste to be disposed of in the repository compared to open-cycle. In the enhanced option, the minor actinides are also recycled and destroyed, further reducing decay heat and ingestion radiotoxicity of the disposed HLW.

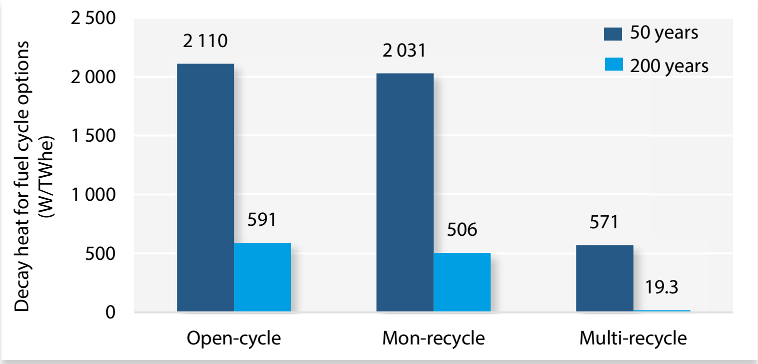
17. Depleted uranium tails assay is residue of fissile uranium-235 remaining in depleted uranium as a result of uranium enrichment.
18. The amount of key caesium and strontium isotopes halves every ~30 years, so after 100 years, the decay heat is reduced by more than 90%.
19. These isotopes decay in half in 88 and 432 years respectively.
20. This is one of the reasons why mono-recycle is often implemented as a first step enabling to move to multi-recycle in the future.

- Summary

UNF reprocessing and reusing nuclear material in reactors reduces the volume of waste, the long-term radiation radiotoxicity, and decay heat capacity needed. If the minor actinides are recycled and consumed, the long-term effects on the performance of geological repositories will be further improved.

Figure 5 is a comparison of decay heat in terms of W/TWhe[21] for fuel cycle options after 50 and 200 years of cooling. The decay heat load is significantly less for multi-recycle, about 25% of that for direct disposal and mono-recycle at 50 years and a negligible amount at 200 years. The 50 year and 200 year time frames are representative of the time when the waste goes to the repository and the time when the majority of the original fission products have decayed. Decay heat typically has a strong influence on the excavation volume and footprint of the underground repository needed.

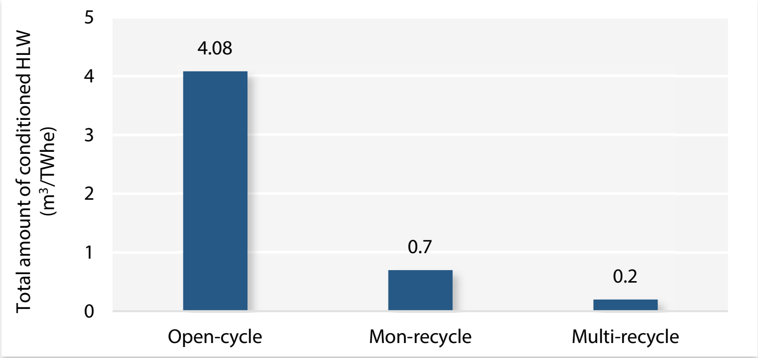
Figure 5. **Decay heat at 50 years and 200 years for fuel cycle options**



Source: *Advanced Nuclear Fuel Cycles and Radioactive Waste Management* (NEA, 2006).

Figure 6 shows the HLW volume to be disposed of for different fuel cycle options. The HLW waste volume is reduced significantly by closed fuel cycle options as compared with the open-cycle. Mono-recycle is 17% of the volume of open-cycle and multi-recycle is 5%.

Figure 6. **High-level radioactive waste volume for the fuel cycle options**

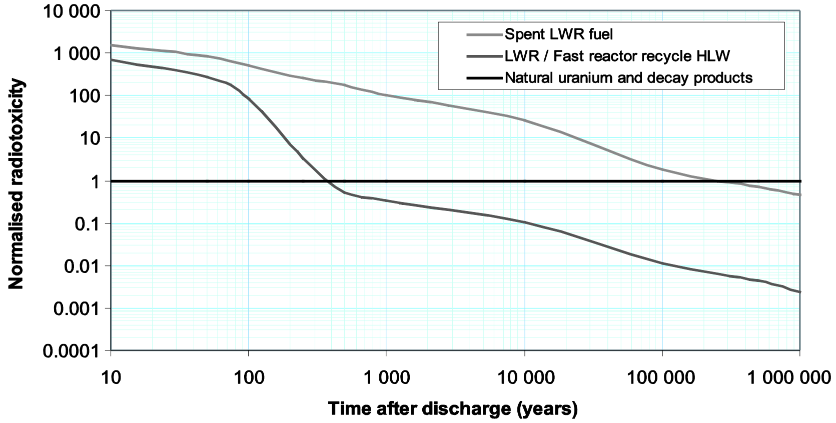


Source: *Advanced Nuclear Fuel Cycles and Radioactive Waste Management* (NEA, 2006).

21. W/TWhe means watt per terawatt hour electricity produced by the nuclear power plants.

It is well known that the time frame before the radiotoxicity of waste in the repository decays to that of natural uranium is hundreds of thousands of years. On the other hand, enhanced multi-recycle with burning all actinides (uranium, plutonium and the minor actinides) could reduce the radiotoxicity of waste down to natural uranium levels within about 400 years (see Figure 7). This is much shorter compared to 300 000 years for SNF in open-cycle and mono-recycle and could reduce the size of the repository required.

Figure 7. **Ingestion radiotoxicity for spent light-water reactor fuel and processing waste where actinides are recovered for recycling**



Source: *Potential Benefits and Impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation* (NEA, 2011).

O.4. Flexibility towards energy independence and security of supply

Using nuclear energy to generate electricity is an effective option for energy independence as it diversifies the sources of primary energy used. Since the energy density of uranium is very high, it is also easy to have stocks for a few years of supply in a very small surface and volume compared to other energy sources, reducing threats to the fuel supply. Identified uranium resources are distributed among 36 countries (NEA, 2019) and this widespread distribution of uranium resources guarantees diversity of supply when domestic sources are insufficient. Of the 30 countries currently using uranium in commercial reactors, only Canada and South Africa produce enough uranium to meet their domestic requirements. For most countries with nuclear power, importing uranium is therefore necessary. The international trade of uranium is well-established. Similarly, there are global markets for front-end and back-end services for commercial reactors.

Open-cycle – A country can utilise the most cost effective combination of domestic mines, uranium conversion, enrichment and fuel fabrication facilities, or corresponding global markets for the front end. For the back-end, domestic or potential shared regional repositories would need to be developed.

Mono-recycle – With a reprocessing and recycling fuel strategy, the proportion of MOX and ERU fuels can be temporarily increased when no national mine exists and the uranium market is under pressure. All UNF from past and current reactor generations constitute therefore a source of valuable materials and equal saving in uranium imports. Furthermore, if no conversion or enrichment plant exists in the country, MOX fabrication can temporarily replace enriched natural uranium fuel if the corresponding markets are tight.

Multi-recycle – Once a multi-recycle nuclear fleet and associated recycle facilities are established, the security of supply is very high because only very small amounts of fertile material are needed to sustain the system, and significant amounts of depleted uranium are typically produced in the process of establishing the fleet. If a country possesses fuel cycle installations then it is totally self-sufficient.

- Summary

Even considering the variety of uranium suppliers and service providers, with no mine or front-end facilities, energy independence is lower for countries that adopt an open-cycle approach. A mono-recycle strategy allows adapting the shares of fuel from enriched natural uranium, ERU or MOX supply driven by the prices in the different global markets. Given an initial inventory of fissile and fertile material, the multi-recycle option significantly reduces reliance on uranium mine and other front-end services, but requires access to reprocessing and recycling facilities. A country with these installations can be totally self-sufficient with regard to the electricity generated from nuclear sources.

O.5. Respecting the interests of future generations

Considering the long time required for the HLW to decay, there is an ethical aspect of leaving this problem to future generations – see Section R.5 later in this chapter. The long time horizon involved translates into higher uncertainty with regard to various parameters, e.g. cost of DGR, changing regulatory conditions, changing socio-political perception of nuclear energy influenced by multiple factors.

Future generations can be assumed to have two fundamental interests related to present day use of nuclear power:

- Avoiding any consequences from today’s decisions that burden future generations with additional costs (including financial).
- Enabling future generations to draw on existing natural resources, whose effective use today is limited by a lack of technical knowledge and/or financial resources.

Open-cycle – Uranium is irradiated only once and, thus, SNF is considered as waste to be disposed of directly after packaging. This avoids the creation of additional waste streams. However, the time frame before the radiotoxicity of waste in the repository decays to that of natural uranium is hundreds of thousands of years (see Figure 7). The DGR is already seen today in a global context as an acceptable solution for this option. Planning for a DGR is often considered a necessary condition for the continuation or development of nuclear energy at national levels. Maintaining the ability to retrieve the waste is often required to not limit future generations’ options (because such materials have some potential for future recycling as a fuel source).

Mono-recycle – Mono-recycle reduces HLW volumes, improves uranium utilisation, and keeps most of the uranium more accessible for potential future reuse (depleted U and recovered U/Th). In this option, the time frame before the radiotoxicity of waste in the repository decays to that of natural uranium is reduced to about 10 000 years and the components can be managed separately.

Multi-recycle – This option can be viewed as an important step towards the technical and social sustainability of nuclear energy and full exploitation of the potential of natural resources. A closed fuel cycle with breeding of fissile material from fertile uranium or thorium can improve natural resource utilisation by a factor of 100. Deployed globally, it could guarantee nuclear fuel resources for at least 1 000 years, while minimising long-term radiotoxicity of nuclear waste (see Figure 7).

- Summary

The interests of future generations are inherent in all of the differentiating characteristics and today’s decisions determine the opportunities, risks and challenges for future generations. The open-cycle with direct disposal in a DGR is the widely accepted reference, although it is not always accepted at the local level. The mono-recycle option provides some additional benefits to future generation. The multi-recycle option represents a significant potential benefit to future generations by providing a proven set of technologies that maximise conservation of natural resources and reduction of long-term radiotoxicity.

2.2.3. *Risks when fuel cycle option is implemented*

R.1. Proliferation

Nuclear non-proliferation has definitely been an important consideration or requirement for securing the acceptance of nuclear fuel cycles and therefore has been recognised as an important factor for policy makers. Generally, the proliferation risk of a specific fuel cycle is mostly often evaluated using its opposite – its degree of proliferation resistance. An internationally accepted definition of proliferation resistance is that "characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices" (IAEA, 2002). The potential security threats or issues posed by non-host-State actors are termed physical protection treated separately under security (R.2).

The principal risks of nuclear proliferation come from the technical characteristics of the nuclear fuel cycle. There are two routes for proliferation risks. The enrichment processes at the front end of the nuclear fuel cycle can be used to produce highly-enriched uranium for use in weapons. On the back end, reprocessing can separate plutonium which can also be used in nuclear weapons. The separation of plutonium at the back end of the fuel cycle carries similar proliferation risks to enrichment of uranium at the front end. This document is focused on the back end, so only discusses ways to reduce proliferation risk in reprocessing.

Non-proliferation has been one of the key issues when considering advanced reprocessing technologies. Different strategies have been explored to resolve this issue. One such strategy includes the partial separation of actinides or fission products to reduce the "attractiveness" of the fissile components but this strategy was found to be only marginally effective. Safeguards-by-design approaches including co-located and integrated UNF or SNF storage, reprocessing separations and recycle fuel fabrication within a physically protected facility are considered as applicable measures to prevent diversion. Physical protection and engineered safeguards are, in any case, necessary (NEA 2018).

Open-cycle – The proliferation risk of the open-cycle arises primarily at the front end because of the demand for large-scale enrichment to make fresh fuels. The back-end risk for this option is much smaller and is based on diversion of SNF assemblies to clandestine reprocessing facilities. These assemblies are large and highly radioactive, making them easy to count by international inspectors and difficult to divert without specialised handling equipment. Geological repository safeguards may be the greatest back-end challenge, since the fuel becomes less hazardous with time and is typically in a configuration that prevents inspection.

Mono-recycle – Current commercial reprocessing plants are based on PUREX which is a proven process and separates uranium and plutonium very efficiently. This separation removes an intrinsic barrier to potential misuse which has historically been regarded as more vulnerable. Process designers have, however, compensated for this by adding systems and processes that limit this vulnerability, such as keeping plutonium and uranium together (co-extraction) to strengthen chemical barriers of proliferation resistance. In addition, sintering of the MOX powder (UO_2+PuO_2) makes it difficult to re-separate Pu. Thanks to reinforced control and surveillance and advanced safeguards approaches, proliferation risks are managed accordingly. Moreover, two cases are to be distinguished: a state can decide to recycle its UNF itself or in another country, which reduces proliferation risks inherent to the consumer state. Proliferation risks are only to be considered when the reprocessing activities are not performed in well-established nuclear countries, i.e. when the necessary development of the reprocessing technology would be on the acquisition path of the reprocessing country.

Multi-recycle – This fuel cycle has the same reprocessing risks as mono-recycle. A number of advanced reprocessing processes have been researched that produce inherently proliferation-resistant products. However, given the resources available to a state, the various plutonium-bearing materials or the reprocessing process itself could be relatively easily converted to produce separated plutonium (NEA 2018). An additional concern is that weapons grade plutonium would be generated in the blanket of the reactor in case of the breeder reactors. In spite of these differences, proliferation risks are related to reprocessing process and therefore can be considered manageable under appropriate safeguards measures as mono-recycle.

- Summary

In general, all fuel cycles have a risk of nuclear proliferation for which the relative degree of the risk has been debated worldwide. Considering the relative attractiveness of materials handled in each fuel cycle option and the effectiveness of the safeguards approached applied accordingly, the differences in terms of proliferation risk are not very significant among three fuel cycle options.

R.2. Security

The International Atomic Energy Agency (IAEA) defines nuclear security as “The prevention and detection of and response to, theft, sabotage, unauthorised access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities”. According to the IAEA definition of physical protection (IAEA, 2002), physical protection (robustness) is that characteristic of a nuclear energy system that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices and the sabotage of facilities and transportation by sub-national entities or other non-host state adversaries. In a broad sense, catastrophic scenarios involving terrorist attacks and cyberattacks are also included. Accordingly, security has a broad meaning covering physical protection and some aspects of nuclear safety. International organisations, national governments and the nuclear industry have long recognised this potential threat and have robust security protocols to secure these materials and the facilities where they are utilised. These measures have been effective since all nuclear fuel cycles have been conducted in a secure manner with sufficient controls and protections.

It is very difficult to differentiate the fuel cycle strategies in terms of nuclear security because the threat will be highly dependent on the specific environment of each country. In this regard, this section considers the different aspects that are inherent to the fuel cycle options, namely the attractiveness and the accessibility of fissile materials that are of interest by sub-national entities or other non-host state adversaries.

Open-cycle – There are considerable physical barriers in the case of the open-cycle, as the fuel is typically maintained in its cladding, either in an underwater storage facility or a large storage, transportation, or disposal cask. The fuel is never in a form that is readily useable, even if it were to be removed by a non-state actor, and it is maintained with the fission products. Its use would require significant technical capabilities to move the material, then convert it to a useable form. It is important to note that, with sufficient protections, the material can be adequately safeguarded and this is routinely achieved today.

Mono-recycle – The recycle options reduce or eliminate one or more of the physical barriers at certain points during the fuel cycle, particularly after the fissile material is separated from the other parts of the fuel and before it is reinserted into a reactor to begin a second irradiation. However, it is important to note that, with sufficient protections, the material can be adequately safeguarded as is routinely achieved currently.

Multi-recycle – There are many different variations of the multi-recycle approach, some of which can be meaningful from a security perspective. In general, the full or multi-recycle option is a little better than the mono-recycle option in terms of material accessibility and material attractiveness, as the UNF is reprocessed by using more proliferation resistant and advanced technology such as co-processing and pyroprocessing.

- Summary

In general, the threat in terms of security highly depends on the specific environment of each country. Considering the different aspects that are inherent to the fuel cycle options, namely the attractiveness and the accessibility of fissile materials which are of interest by sub-national entities, the open-cycle with self-protection of nuclear material may be a little better than other fuel cycle strategies. However, it is important to recognise that after long-term storage and during disposal of SNF, attractiveness may increase due to collapse of radiation self-protection as decay of fission products decreases radiation self-protection. That may increase attractiveness and accessibility of SNF and UNF.

R.3. Worker safety

In addition to traditional industrial risks, nuclear installations have to take into account protection against ionising radiation exposure. Its main principles are established at the international level (ICRP, UNSCEAR). National regulations are established to provide a radiological protection framework consistent with these principles. Within this framework, operators develop their own internal procedures to manage worker exposures on a case by case analysis basis. Throughout the world, occupational exposures at nuclear power plants and nuclear cycle facilities have steadily decreased since the early 1990s. Regulation evolution, technological advances, improved equipment designs, advanced material/component and operational procedures, the as low as reasonably achievable principle and information exchange have contributed to this downward trend. A side benefit to the safety culture associated with radiation safety is spill-over to include traditional industrial risks, making nuclear jobs among the safest in any industry.

The occupational doses to workers in the whole fuel cycle are dominated by doses at the nuclear power plants, and are not affected by the type of fuel used (UO_2 or MOX fuel) (NEA, 2001). Doses to workers in nuclear installations have been reduced over the years, efforts will continue in this direction even though dose levels are well below regulatory limits (NEA, 2020; IAEA, 2014,). The remaining dose mainly comes from mining activities with ore extraction and uranium concentration. At the fuel fabrication stage, there are differences between doses exposure for the open-cycle and mono-recycle due to MOX fuel, however these doses represent only a small fraction of the sum over the whole fuel cycle.

Open-cycle – After irradiation, SNF is cooled pending transport to an interim storage facility and after, to a future DGR. Worker exposure primarily occurs during handling operations when SNF is being transferred between different shielding systems. Depending on the availability of the DGR, SNF may have to be handled several times, including potential fuel repacking requirements prior to transportation and/or disposal.

Mono-recycle – In this strategy, the reprocessing of UNF decreases the need for natural uranium mining and the corresponding worker exposure. On the other hand, the dedicated installations, storage and transports to reprocess UNF and manufacture fresh fuel from recycled materials represent a minor share of the worker exposure in the nuclear fuel cycle. In reprocessing plants, most of the process is performed by remote handling devices. The operations lead to a low workers annual exposure which is below the exposure of nuclear power plant employees. Continuous improvement has been a major objective of existing mono-recycle facilities and has driven innovation and R&D to reduce workers exposure in these fuel cycle installations as well as for recycled materials storage and transport. New technologies for remote handling devices and robotics are leading to continuous dose exposure reduction much below the regulatory dose limitations which benefit the whole nuclear industry. As a result, the global worker exposure is decreasing.

Multi-recycle – The multi-recycle approach constitutes a major opportunity for the safety of the nuclear sector and for innovation in the development of exposure reduction means. Furthermore, with no need for natural uranium, there is no worker exposure associated with ore mining.

- Summary

Worker safety in the nuclear industry and in particular radiation protection is a multi-factor issue: regulations, technology, economics, procedure and culture can contribute to monitoring and reducing worker exposure. Collective doses in the whole fuel cycle, normalised to electricity production, are dominated by those at the power generation stage, and are not affected by the type of fuel used. Regarding back-end strategies, although the main difference concerns the fuel fabrication stage, this represents only a small fraction of overall doses. Compared to open-cycle, in the mono- and multi-recycle strategies, uranium mining necessary is reduced as well as the associated exposure. As is the case for other nuclear fuel cycle activities, existing facilities for reprocessing UNF and MOX manufacturing have demonstrated continuous improvement in worker exposure, through innovation and R&D efforts in human factors fields and technologies, and thereby benefitting the whole nuclear industry. The differences between open and mono-recycle regarding worker exposure are very small, radiological impact to workers is not a key factor favouring one or the other option.

Managing safety is a common issue for all options and a similar level of safety could be achieved in each fuel cycle option with the adequate actions. Annex D describes managing safety related to the ongoing transition to the 2016 IAEA safety standards introduced in the wake of the Fukushima-Daiichi accident (IAEA, 2016).

R.4. Public and environmental safety

Nuclear fuel cycles have several potential impacts on public and environmental safety. Focusing on the public first, the impact that most people think of is radiation. However, this is actually not the greatest risk to the public. The greatest risk comes from trucks transporting fuel and fuel feedstock (e.g. uranium), not due to the contents of the trucks but just due to the trucks themselves being on the road, whether full or empty. In an accident involving any large truck, other smaller vehicles are more likely to be damaged and their occupants injured or killed independent of who or what causes the accident. The public is very unlikely to be harmed by radiation associated with the fuel cycle, since the fuel and fuel components spend most of the time at nuclear facilities behind fences and walls and during the short periods when these materials are being shipped, they are inside packages with appropriate shielding that have been designed to survive even the most severe of traffic accidents. The other risk to the public is the long-term risk from long-lived waste being introduced into the environment.

The primary impact to the environment is the disturbance to the land caused by mining of uranium. With proper remediation after closure, mining impacts can be minimised. The other risk is again the long-term impact from disposed waste leaching into the environment. Potential accidents at facilities could also result in local soil and groundwater contamination that would require remediation.

The primary differences in public and environmental impacts between the different fuel cycle options are due to the amount of uranium mining required and the amount and types of waste to be disposed along with any differences in their characteristics.

Open-cycle – The open-cycle requires the most uranium mining of the different fuel cycle options. It also requires the most shipping of fuel materials due to the relatively larger amount of shipping of natural, depleted, and enriched uranium on the fuel cycle front end. The hazard and longevity of the waste (in this case, SNF and depleted uranium) is also the greatest because nothing has been consumed except for some uranium. However, there are fewer back-end facilities, and no chemical separation facilities to potentially contribute to environmental contamination.

Mono-recycle – Reprocessing of UNF presents some hazards not included in the open-cycle, including additional waste streams and an increased potential for environmental contamination. However, reductions in the amount of uranium mining (by about 25%) and in front-end shipments (again by ~25%) have a larger, positive safety impact. The HLW resulting from reprocessing also has some hazards removed and uses a longer-lasting waste form (glass) than straight SNF in most environmental situations, thereby also reducing the potential long-term impact. The direct disposal of spent MOX fuel limits this improvement. However, a properly designed geological repository will minimise any long-term risk to the public from either SNF or HLW.

Multi-recycle – Like for mono-recycle, reprocessing of UNF presents some hazards not included in the open-cycle. The very large reduction in uranium mining (over 99%) and associated materials shipping will reduce front-end impacts to both the public and the environment. In addition, the consumption of plutonium and depleted uranium in the fuel cycle will reduce long-term hazards. A smaller increase in back-end shipments will somewhat moderate the front-end improvements. Enhanced multi-recycle has the least public and environmental safety impact overall, although most of the impacts are unchanged from the multi-recycle of plutonium option. The multi-recycle impacts on mining and shipping of materials will be mostly unchanged, but the consumption of minor actinides and long-lived fission products will decrease long-term radiotoxicity.

- Summary

The public is very unlikely to be harmed by radiation associated with the fuel cycle, since the fuel and fuel components spend most of the time at nuclear facilities, which are equipped with radiation shields and other safety barriers. The other risk to the public is the long-term risk from long-lived waste entering the environment. The primary impact to the environment is the disturbance to the land caused by the mining of uranium. With proper remediation after closure, mining impacts can be minimised. The primary differences in public and environmental impacts between the different fuel cycle options are due to the amount of uranium mining required and the amount and types of waste to be disposed along with any differences in their characteristics. In this regards, the open-cycle strategy requires the most uranium mining of the different fuel cycle options and their shipment.

R.5. Sustainability

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). Access to affordable, reliable and clean energy is crucial for achieving sustainable development goals, from eradicating poverty through advancing health and education, facilitating industrial development and reducing greenhouse gas emissions to limit climate change. Nuclear power can provide the energy to achieve high living standards, good health, a clean environment and a sustainable economy. The analysis of nuclear energy characteristics within a sustainable development framework shows that the approach adopted by the nuclear energy sector is generally consistent with the fundamental sustainable development goal of passing on a range of assets to future generations while minimising the financial and environmental impacts. Sustainable development depends on the long-term availability and environmentally sound production of fuel and SNF management.

Open-cycle –Historically, concerns about the depletion of uranium resources have been mitigated by technological improvements in the mining industry and current global uranium resources are found as adequate to meet demand for decades. However, its future availability depends upon timely investments to turn resources into refined uranium ready for nuclear fuel production, which can be constrained by continuing pricing pressures and concerns associated with geopolitical factors, technical challenges and legal and regulatory frameworks (NEA 2019). Sustainable development also means safe disposal of all nuclear waste including depleted uranium stored at enrichment plants. There is wide consensus that dealing effectively with waste to achieve high levels of safety and security is desirable in a 50-year perspective, ensuring that each generation deals with its own waste.

Mono-recycle – By mono-recycle, the uranium and plutonium in UNF and the uranium demand can be diminished by about 25%, improving the sustainability of natural resources. The reduction in the uranium demand has several positive environmental and economic aspects: the environmental effects of uranium mining is reduced seen per kWh produced; the uranium resources will last longer; there will be less front-end activities, in particular the needs for enrichment will decrease; and electricity costs will be less sensitive to the uranium price.

Multi-recycle – By multi-recycle, there is a potential to reduce the uranium demand by over 95%. Also the depleted uranium from the enrichment process will become an important fuel source. Enhanced methods for efficiently recycling the UNF (including HLW partitioning) will reduce the radioactive hazards as well as the volume of the waste that must be kept isolated from the environment. When implementing the latter, the level of radioactivity of a repository containing this type of waste after about 400 years will be comparable to that of the natural uranium deposits. In this way, the much-publicised radioactivity issue of the waste will be reduced to a historical time scale of a few hundred years, rather than a geological time scale of hundreds of thousands of years. It is important to note that this waste will be disposed of in an environmentally inert form, i.e. ceramic or vitrified solids that will not start leaching any material into the environment for thousands of years.

- Summary

The analysis of nuclear energy characteristics within a sustainable development framework shows that the approach adopted by the nuclear energy sector is generally consistent with the fundamental sustainable development goal of passing on a range of assets to future generations while minimising environmental impacts. Sustainable development depends on the long-term availability and environmentally sound production of fuel and SNF management. In this regard, the open-cycle is relatively less sustainable as it uses more natural resources and produces more long-lived HLW than other fuel cycle options. The enhanced multi-recycle option transforms uranium into a truly inexhaustible energy source, while new radioactive waste management technologies reduces radiotoxicity of waste down to natural uranium levels within a few hundred years.

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Chapter 3. **Back-end strategies for different countries**

This section describes the current situation of each country represented in the NEA expert group. It includes:

- the number of nuclear power reactors shut down, operating, under construction, and planned;
- the back-end strategies being deployed or under development and their status.

Table 2 summarises the current situation in each country and is grouped by characteristics that may influence their decision making and set them apart from other countries. Following the table is a brief description of each country's current situation. More detailed descriptions on back-end strategies in different countries are provided in Annex A.

Table 2. **Status in each country**

Country	Power reactors	Open-cycle		Mono-recycle	Multi-recycle and waste minimisation
		Policy decision/ determination of geological disposal site	Ownership and Responsibility of final disposal		
3.1. Small programmes, phasing out					
Belgium	7 operating. All to phase out by 2025.	Policy not decided and hence site to be determined.	Owned and operated by private companies.	Reprocessed 670 MTHM but ceased operation.	Domestic R&D and international collaborations.
3.2. Small programmes, continuing					
Czech Republic	6 operating. 3 or 4 planned to increase nuclear share from 30% to 50%.	Yes. Site to be determined. Operational in 2065.	Reactor operator funded. Government implements.	Mixed oxide fuel under consideration for new units.	International collaboration for Generation IV.
Hungary	4 operating. 2 planned.	Policy not decided but site undergoing characterisation. Operational in 2064.	Reactor operator funded. Public agency implements.	No.	International collaborations.
3.3. Large programmes, no active reprocessing					
Korea	1 shut down. 24 operating. 5 under construction.	Policy not decided but site to be determined and operational in 2053.	Reactor operator funded. Public agency implements.	No.	Domestic R&D and international collaborations.
United States	30 shut down. 96 operating. 2 under construction.	Yes. Site established. Licensing suspended.	Reactor operator funded. Government implements.	No.	Domestic R&D and international collaborations.

Note: MTHM - Metric tonnes heavy metal; R&D - research and development.

Table 2. **Status of each countries** *(cont'd)*

Country	Power reactors	Open-cycle		Mono-recycle	Multi-recycle and waste minimisation
		Policy decision/ determination of geological disposal site	Ownership and responsibility for final disposal		
3.4. Large programmes, active reprocessing					
Japan	24 shut down. 33 existing. (9 of them restarted) 3 under construction.	No.	-	Industrial-scale mono-recycle will start in near future.	R&D in progress.
France	13 shut down. 58 operating. 1 under construction.	No.	-	Yes. Industrial-scale mono-recycle in operation.	R&D Projects under way to demonstrate industrial multi-recycle.
Russia	35 operating. 11 planned.	No.	-	Yes. Industrial-scale mono-recycle in operation.	Projects under way to demonstrate multi-recycle.

3.1. Small programmes, phasing out

3.1.1. *Belgium*

In 1993, the Belgian parliament asked the private operator in charge of and hence owner of the nuclear fuel, SYNATOM, to suspend its reprocessing contracts and to not negotiate any new contract without its approval (in total, 670 metric tonnes heavy metal [MTHM] had been reprocessed). Since 1993, Belgium considers the open-cycle and mono-recycle equivalent options. The current reference scenario of the fuel's owner is that reprocessing for ~25% of the total amount of spent nuclear fuel (SNF) is foreseen at the end of operations and the open-cycle for the remaining SNF.

Since 2011, European Union countries are subject to the European Council Directive 2011/70 (EC, 2011). Inter alia, this Directive establishes the framework for the management of SNF. Belgium published its first national programme in 2015 which specifies that the reference policy (national policy) for the management of SNF from commercial nuclear power plants is its safe storage followed by reprocessing or disposal. ONDRAF/NIRAS therefore continues its research, development and demonstration on the geological disposal of both SNF and reprocessing waste. In early 2020 a public consultation concerning the geological disposal of radioactive waste and SNF was launched. In the meantime, the country supports the research on waste minimisation through partitioning and transmutation enacted by its decision to build the MYRRHA research infrastructure.

3.2. Small programmes, continuing

3.2.1. *Czech Republic*

Back-end strategies are based on the "National Strategy on Radioactive Waste and Spent Nuclear Fuel Management" in the Czech Republic, rev. 1 (approved 2014, rev. 0, 2002). Site selection for the deep geological repository is scheduled according to a government-approved timetable. Currently, the evaluation of nine candidate sites is being finalised with a proposal to reduce their number to four for further more detailed assessment. SNF is stored in interim storages at the sites of power plants. The fuel is stored in dry-type containers, designed for 50 years of service life. There is a backup underground location for a central fuel storage that can be used (in case of new units being constructed) to bridge the need for storage from the end of operation of existing units to the opening of the deep repository.

The Czech Republic is actively involved in generation IV (Gen IV) reactor research activities on both the national and international level. Such involvement includes: participation in the ALLEGRO Project (gas-cooled fast reactor demonstrator), newly constructed experimental loops (super critical water loop [SCWL], high temperature helium loop [HTHL], liquid metal Pb-Bi loop), the loop using Pb-17Li for studying of the ITER Fusion Tokamak cooling, or testing of molten salt properties as a Molten salt reactor or fluoride salt-cooled high-temperature reactor coolant. The conceptual design of a small-modular reactor using the molten salt as a primary and secondary coolant, is being developed. However, no commercial radiochemical treatment of irradiated fissile material or SNF is planned in the Czech Republic in the future.

3.2.2. *Hungary*

The Public Limited Company for Radioactive Waste Management (PURAM) is responsible for the implementation of national policy and national programme, including final disposal of radioactive waste and interim storage of SNF, and the back end of the fuel cycle. No final decision has been taken yet on the back-end strategy for the closure of the nuclear fuel cycle. A staged site investigation programme for a deep geological repository has been developed and currently a surface-based geological research programme is ongoing. Interim storage of SNF from Paks I is in the Spent Fuel Interim Storage Facility in Paks. The storage is a modular vault dry storage type facility, the capacity of the facility has been and will be further extended as necessary.

Hungary is actively involved in international fast reactor research activities, including the ALLEGRO Project to design, build and operate the first gas-cooled fast reactor demonstrator in the Central European region. The corresponding roadmap of the design works and safety analysis is being defined and the conceptual design is due to be completed by 2025. Hungary will host the advanced fuel research activities, and will therefore construct a Fuel Institute with the necessary infrastructure.

3.3. Large programmes, no active reprocessing

3.3.1. *Korea*

In Korea, the national policy for SNF management has not been decided. In 2015, the Public Engagement Commission on Spent Nuclear Fuel Management (PECOS) recommended the implementation plan for SNF management to the government after a series of public deliberations, including international seminars and town hall meetings held over a period of nearly two years. In 2016, the Ministry of Trade, Industry and Energy (MOTIE) announced a basic plan for high-level radioactive waste (HLW) management based on the PECOS recommendation. The mono-recycle option is not considered in Korea due to the non-proliferation issue. However, Korea is working on the research and development (R&D) of pyroprocessing in combination with the sodium-cooled fast reactor for the minimisation of a repository size and the toxicity of the SNF. For pyroprocessing, Korea is collaborating with the United States through a ten-year long Joint Fuel Cycle Studies (JFCS) agreement until 2020 to check the technical feasibility, economic viability, and non-proliferation acceptability of the process. After the end of the JFCS, the Korean government will take a decision on whether or not to continue R&D on the pyroprocessing and the sodium-cooled fast reactor technology.

3.3.2. *United States*

The Nuclear Waste Policy Act of 1982 (NWPA) directs the US Department of Energy (DOE) to site, construct, and operate a geological repository for SNF and HLW. The 1987 amendments to the NWPA directed DOE to focus its efforts solely on Yucca Mountain. The DOE determined in 2002 that Yucca Mountain would be a suitable location for a repository. Later that year, Congress and the President endorsed that decision through enactment of a joint resolution approving the site. A licence application for a geological repository at Yucca Mountain, Nevada is pending at the US Nuclear Regulatory commission (NRC).

Most of the US nuclear power plants are storing SNF in NRC-licensed independent spent fuel storage installations (ISFSIs) located on-site. Most permanently shut down commercial reactors currently have, or are planning to have, their SNF stored at on-site ISFSIs pending disposal. There has been commercial interest in consolidated interim storage, with two applications under review at the NRC.

Regarding reprocessing, the United States briefly deferred the pursuit of reprocessing commercial used nuclear fuel (UNF) in the 1970s over proliferation concerns. That policy was later reversed but commercial reprocessing has never been pursued by private industry. The US government continues to invest limited resources into research and development on reprocessing technologies focused on cost reduction, waste management resulting from reprocessing, and material protection, accountancy, and control technologies related to reducing proliferation risk. However, there is no compelling need within the United States at this time to increase that investment or offer incentives to private industry to pursue commercial reprocessing.

3.4. Large programmes, active reprocessing

3.4.1. Japan

As stated in the "Strategic Energy Plan", which was adopted by the Cabinet in 2018, the basic policy of Japan is to promote a nuclear fuel cycle that reprocesses UNF and effectively utilises the plutonium retrieved, from the viewpoint of effective utilisation of resources and reduction of the volume and harmfulness of HLW.

Up to date, UNF have been reprocessed domestically in the active test at the Rokkasho Reprocessing Plant (RRP, under construction), and the RRP is scheduled to start operating in the first half of the 2021 fiscal year, and has a reprocessing capacity of 800 MTHM per year. The plutonium reprocessed in Japan will be fabricated into mixed oxide (MOX) fuel in the MOX Fuel Fabrication Plant adjacent to the RRP, which is scheduled to operate in the first half of 2022 fiscal year. Currently, four reactors are loading MOX fuel, and six more reactors that planned to load MOX fuel are applying for the regulatory process to restart.

The government will continue with research and development related to measures for the reprocessing and disposal of used or spent MOX fuel and consider the issue in light of the status of the generation and storage of used or spent MOX fuel, trends of reprocessing technologies, and the intentions of relevant municipalities. As for waste minimisation, research and development is being undertaken. The introduction of a fast reactor is being pursued, and further research and development will be conducted in accordance with the Strategic Roadmap for Fast Reactor Development.

3.4.2. France

The reprocessing of UNF is a high priority embodied by the development of an industrial know-how. Every year, about 120 MTHM of MOX fuel is produced to be used in the EDF nuclear fleet (24 reactors have the authorisation to use MOX fuel). This fuel is produced by the Melox plant in Marcoule. The plutonium is separated at La Hague plant which reprocesses annually around 1 100 MTHM of UNF to meet the MOX demand.

The 2019 Multiannual Energy Plan confirms that the closed fuel cycle is of strategic importance for the country. Furthermore, mono-recycle strategy is to continue until at least 2040. The ultimate goal is to enable the multi-recycle of UNF. In France, the generation IV sodium-cooled fast reactor is the current reference option. However, the potential deployment of a fleet of sodium-cooled fast reactors is expected in the second half of the 21st century. Therefore, the R&D programme to support the closure of nuclear fuel cycle will focus on assessing value and feasibility of the multi-recycle of used fuels in light-water reactors in the medium term, while maintaining research carried out by the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) to prepare the potential development of a future sodium-cooled fast reactor system.

3.4.3. *Russia*

The core principle of the state policy of Russia in the field of SNF management involves SNF reprocessing to prevent SNF accumulation, to recycle the nuclear material by recovering the remaining energy resource of the SNF and reducing uranium demand, and to ensure the environment-friendly management of radioactive waste (fission products and minor actinides). The task of ensuring the safe management of radioactive waste is considered to be, on the one hand, a key element of the national security and safety, and, on the other hand, an essential precondition for present and future use of atomic energy. The "Energy Strategy of Russia for the Period up to 2030", approved by the Russian government, includes the development of advanced radioactive waste treatment methods and technologies and ensuring a closed nuclear fuel cycle where the rate of waste accumulation is equivalent to the rate of waste disposal. Centralised SNF management with reprocessing is provided at two sites: PA Mayak and Mining & Chemical Combine (MCC). For the development of sustainable fuel cycles and waste management, Russia has R&D and industrial activities with both thermal and fast reactors. Russia has started Pu multi-recycling based on MOX fuel used in BN-800 fast reactor. MOX fuel fabrication for BN-800 is produced in a MOX fuel fabrication facility at MCC.

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Chapter 4. Decision drivers

Chapter 2 described the fuel cycle options and then their characteristics that would factor into decision making in pursuing one or the other options. Chapter 3 described the current situation of each country represented in the expert group: what back-end strategies are being deployed and why? This chapter examines issues not included previously that would also be important considerations for policy makers.

4.1. Back-end strategy: The IAEA Joint Convention and EU Directive

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management was adopted in 1997 at a conference convened by the International Atomic Energy Agency (IAEA). Under the Joint Convention, the contracting parties commit to applying stringent safety measures, to preparing a national report on the applied measures and submitting it for review by all other contracting parties.

The European Council Directive 2011/70/Euratom, i.e. the EC Directive, establishes a community framework for the responsible and safe management of spent nuclear fuel (SNF) and radioactive waste. The EC Directive requires member states to prepare a policy expressed as a national programme for managing SNF and radioactive waste up to the disposal of all waste. The programme has to describe the needed facilities and all activities connected to their implementation, including research and development (R&D) and has to be implemented in a timely manner. The EC Directive ensures adequate public involvement as well as arrangements for a high level of safety in SNF and radioactive waste management.

Both the Joint Convention and the EC Directive states that final waste should be disposed of in the country where it is generated. Although the final responsibility for the management of radioactive waste lies with each member country, they accept that in certain circumstances, safe and efficient management of SNF and radioactive waste might be fostered through agreement among countries to use facilities in one of them for the benefit of the others, for instance two or more member countries can agree to share a final repository located in one of them. Radioactive waste from Luxemburg being stored in Belgium would be one example.

In 2015, EU member states notified the European Commission on their national programme for SNF and radioactive waste management and provided their first national reports on implementation of the EC Directive. The European Commission prepared in 2017, based on those reports, the first Report to the Council and the European Parliament on progress of implementation of EC Directive. Every three years, member states are to provide updated national reports on the implementation of the EC Directive and corresponding national programmes status, including any substantial changes.

4.2. Extended storage of spent nuclear fuel

Both the open-cycle and the mono-recycle fuel cycle (if not pursued with multi-recycle option) require disposal of SNF. At present, there is no operating SNF (nor High-level radioactive waste [HLW]) disposal facility in the world. Therefore, some SNF has been in storage for more than 60 years. Disposal of SNF involves an extremely long period of time for siting a repository, construction, and emplacement of the SNF. Prolonged decision making over back-end fuel cycle strategies also adds to the time required to store SNF.

Policy makers should carefully consider the following factors when selecting a fuel cycle option and designing a process for final disposal of SNF should that be required. These factors can become formidable challenges as the period of time required for SNF storage is extended over a long period of time (IAEA, 2019).

- Safety: Both storage underwater and in dry storage have been proven to be safe. However, SNF or the waste packages that contain them may lose integrity over an extended period of time. The SNF will require ageing management plans to monitor the condition of the SNF and include mitigation plans should degradation mechanisms become evident.
- Land use: Property must be set aside for the duration of SNF storage and include adequate physical protection. Over an extended period of time this may impede the redevelopment of property.
- Logistics: Eventually the SNF needs to be transported from storage to a treatment or disposal facility. Available handling and transportation options may change over an extended period of time.
- Impediment to nuclear energy expansion: Extended storage of SNF could become a major impediment to the future expansion of nuclear energy due to an inability to dispose of SNF from existing reactors.
- Costs: All of these factors add to the costs of SNF management and will multiply over an extended period of time.

4.3. Country characteristics

It is evident from Chapter 3 that each country has somewhat different approaches to the back end of the fuel cycle and different reasons for pursuing their approach. This section explores the characteristics of countries in two dimensions to provide insights into the decision-making process for policy makers to consider. The first characteristic has to do with the size of a country's nuclear power programme: large programmes with ten or more power reactors and small programmes with fewer than ten power reactors. The second characteristic has to do with the direction the country's nuclear power programme is headed: stable and ongoing, phasing out, or under developed.

4.3.1. Size of nuclear power programme

Countries with large nuclear power programmes have large quantities of used or spent nuclear fuel (UNF or SNF) to manage. That leads to favourable economies of scale when considering the fuel cycle options. A few sites and a few facilities can store, process, and/or dispose of a large quantity of SNF. Countries with large nuclear power programmes will also have an established infrastructure and technical expertise that developed their large nuclear power programme in the first place. That infrastructure and technical expertise will be available to also develop the programmes needed to manage the back end of their fuel cycle.

Conversely, countries with small nuclear power programmes have small quantities of UNF or SNF to manage. In that case it can become extremely costly to develop the programmes that would be required to manage a small amount of SNF. Also, their infrastructure and technical expertise may not be adequate to develop programmes needed to manage the back end of their fuel cycle without considerable additional investments.

4.3.2. Direction nuclear power programme is headed

Countries with stable and ongoing nuclear power programmes are looking at continued operation of their existing power reactors well into the future and may even have plans to increase the production of nuclear power. Even if they foresee stable or even declining production, they will still be generating SNF well into the future. So, these countries need to factor that increasing generation of SNF into their decisions on the back end of the fuel cycle. The urgency in making decisions and developing programmes today may not be great but that will grow with time and back-end programmes take a long time to develop.

Countries phasing out their nuclear power programmes will see a declining generation of SNF eventually to zero. However, they are also faced with a declining infrastructure and technical expertise as reactors shut down. They also face the challenge of having to invest in a SNF disposal solution well after the benefits of nuclear power production has ended. This may lead to extended storage of SNF and the challenges described in Chapter 4.1 above.

4.3.3. *Countries with nuclear power programmes under development*

Countries with nuclear power programmes under development are focusing primarily on bringing their first power reactors on line. This involves developing the capabilities to select reactor technologies, site the plant(s), and oversee the design, construction, and operation. Management of SNF and the back end of the fuel cycle is an important consideration at these early stages of development as well. Even countries with nuclear power programmes under development need to develop strategies for the back end of the fuel cycle. These countries could benefit now from international collaboration with countries with large and small nuclear power programmes to understand the challenges of the back end of the fuel cycle and the type of investment that will be required in the future.

4.4. Shared infrastructure and international co-operation on used or spent fuel management

Almost from the start of nuclear power industry, international co-operation took place. Early initiatives from the 1950s led to the founding of the IAEA, where the initial focus of international collaboration was on the front end of the nuclear fuel cycle, back-end issues were to be taken up at a later stage. There may be considerable advantages in cost, safety, security and non-proliferation gained from international co-operation in the back end of the nuclear fuel cycle. Both the Joint Convention and the EC 2011 directive on SNF and radioactive waste management accept international co-operation under certain circumstances. Safe and efficient management of SNF and radioactive waste might be fostered through agreement among countries to use facilities in one of them for the benefit of the others.

If SNF and/or HLW can be collectively reprocessed or stored and disposed of in multinational infrastructures to be intensively monitored and well protected, security and safety concerns about nuclear materials can largely be reduced. Technically and economically, the potential benefits of multinational facilities are broadly recognised, but their implementation depends on political support in the countries concerned.

The initial phase of the multinational co-operation focused on recycle strategies and minimising nuclear fuel cycle infrastructure among interested partners leading to shared investment in recycling facilities in France and in the United Kingdom at the end of the 1980s. Reprocessing of significant amount of UNF has been largely and successfully implemented on a multinational basis, demonstrating the feasibility of this approach for the back end of the fuel cycle. The possibility to have reprocessing carried out abroad is a first step towards multilateral co-operation on the back end of the fuel cycle. Today, this is an available strategy choice for any country with a nuclear power programme, since reprocessing services are currently offered by France and Russia.

Multilateral interim storage infrastructures could become an option if nuclear power continues to expand. However, the incentive for countries to develop multinational storage facilities may not be seen as high, unless it is associated with future multinational disposal.

Building a national deep geological repository is a tremendously difficult challenge to many countries, and accordingly, a multilateral approach to the back end of nuclear fuel cycle has been regarded as an attractive option. There is a long history of shared disposal initiatives since the 1970s, so far all failed for political, technical and economic reasons. Thus, there has been very limited co-operation on implementing radioactive waste disposal although co-operation between waste management organisations in different countries is well established but limited to the area of research and development. The issue of importing radioactive waste remains very sensitive, and is even currently forbidden by law in several countries including Finland and Sweden (TEM, 2015; IAEA, 2004). Such a large-scale multinational project, highly technical in nature and demanding innovative investment, extending over several decades, is politically and socially sensitive. Technical, financial, institutional, and socio-political issues will have to be overcome. The technical and economic challenges may in fact be more easily addressed by several partners than by a single nation. Nevertheless, the uncertainties are principally of a socio-political nature and are undoubtedly greater in multinational projects. Finally, the level of complexity of such a project is probably very different when considering shared repositories of HLW using universal canisters following reprocessing of UNF alleviating many challenges compared to shared SNF direct disposal option. This option could be reached through multinational collaborations all along the back end of the fuel cycle.

More information on shared infrastructure is provided in Annex C.

References

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TEM (2015), *"Management of spent fuel and radioactive waste in Finland – national programme in accordance with Article 12 of the Council Directive 2011/70/Euratom"*, Ministry of Employment and the Economy, Energy Department, Finland.

Chapter 5. Conclusions and recommendations

The previous chapters provide descriptions and differentiating characteristics of the fuel cycle options (Chapter 2), case studies from the countries represented in the expert group (Chapter 3), and other important information for policy makers to consider (Chapter 4). This section summarises the significant conclusions derived from the report and recommendations for future action. The conclusions and recommendations refer to earlier sections where applicable.

5.1. Fuel cycle options can be reduced, in a first approach, to three: Open-cycle, mono-recycle and multi-recycle

Based on physics and the processing of material through the fuel cycle, fuel cycle options can be reduced to three: open-cycle, mono-recycle, and multi-recycle. Multi-recycle can be enhanced by the transmutation of the minor actinides. Open-cycle uses low enriched uranium in light-water reactors and disposes of the spent nuclear fuel (SNF) in a deep geological repository. Mono-recycle reprocesses the used nuclear fuel (UNF) once to produce mixed oxide fuel (MOX) (depleted uranium and plutonium) and enriched reprocessed uranium (ERU) fuel that are again used in light-water reactors. High-level radioactive waste (HLW) from reprocessing and the spent MOX and ERU fuel is disposed of in a deep geological repository. Multi-recycle introduces fast spectrum reactors to use fuel from multiple reprocessing cycles. Only the HLW from reprocessing is disposed of in a deep geological repository. No UNF is disposed of as long as the fuel cycle is active. Multi-recycle can be enhanced by the transmutation of the minor actinides to reduce the amount of long-lived radionuclides requiring disposal (Section 2.1).

5.2. There are challenges, opportunities, and risks that are shared by all fuel cycle options to a similar degree

All fuel cycle options require deep geological disposal and none of those are operating anywhere in the world. The open-cycle option disposes of SNF. The mono-recycle option disposes of HLW from reprocessing and in case subsequent multi-recycle option is not pursued, spent MOX and ERU fuel. The multi-recycle option disposes of HLW from reprocessing. No country will complete any of these options until they have a deep geological repository operating to dispose of their SNF and/or HLW (Chapter 2.1).

All of the fuel cycle options share other developmental challenges such as financial challenges (Section 2.2.1[C.2]) and social acceptance (Chapter 2.2.1[C.4]). They also share a number of implementation risks such as proliferation (Chapter 2.2.3[R.1]), security (Chapter 2.2.3[R.2]), worker safety (Chapter R.3), and public and environmental risk (Chapter 2.2.3[R.4]). The extent of these developmental challenges and implementation risks are not so different among the fuel cycle options to make them discriminators when comparing the options.

5.3. Some challenges, opportunities, and risks are significantly different among the fuel cycle options

The amount of natural uranium required at the front end of the fuel cycle is significantly different among the fuel cycle options. The mono-recycle option reduces the amount of natural uranium by 25% compared to the open-cycle option. The multi-recycle option leads to a 99 reduction or more. (Chapter 2.2.2[O.2]) This could have a positive impact on preserving natural resources (Chapter 2.2.2[O.2]) and energy independence (Chapter 2.2.2[O.4]).

The characteristics of the material that requires disposal is also significantly different among the fuel cycle options. The volume of HLW is significantly less for mono-recycle and multi-recycle compared to open-cycle. Mono-recycle is 17% of the volume of open-cycle and multi-recycle is 5%. The decay heat load is significantly less for multi-recycle, about 25% of that for direct disposal and mono-recycle at 50 years and a negligible amount at 200 years. Finally, the radiotoxicity of the material requiring deep geological disposal is significantly less for enhanced multi-recycle, decaying to that of natural uranium in about 400 years compared to 300 000 years for SNF in open-cycle and mono-recycle (Chapter 2.2.2[O.3]).

Technical challenges are much greater for multi-recycle. That fuel cycle requires the development and operation of fast reactors on a commercial scale. (Chapter 2.2.1[C.1]) On the other hand, the economic development opportunities are greater for multi-recycle. It requires more complex technologies and facilities along with a more educated workforce and higher paying jobs (Chapter 2.2.2[O.1]).

5.4. All countries need to be actively implementing a strategy for the back end of the fuel cycle

Both the European Union and the International Atomic Energy Agency have called on every country to develop a national programme for the management of SNF and HLW up to the disposal of all waste (Chapter 4.1). Prolonged delays in making decisions and in implementing decisions that have been made increase costs and the probability of failure (Chapter 2.2.1[C.2]; Chapter 4.2). It further transfers the burden to future generations (Chapter 2.2.2[O.5]). It also harms the prospects for countries to reap the benefits of nuclear power in the future (Chapter 4.2).

There is no optimal solution that would drive all countries to a common fuel cycle or back-end strategy. Countries have made their decisions up to this point based on their history of nuclear power development and the values they place on the different characteristics of the fuel cycle options and their view on the long-term use of nuclear power. (Chapter 3; Chapter 4.3). Energy policy may also evolve with time leading to change from a reference solution to another option.

5.5. All countries need to invest in knowledge management

The period of time required to implement any fuel cycle option through until the final disposal of waste is extremely long. There are multiple technology options, some with high technology readiness levels available today and others with low technology readiness levels that will require additional research and development. Without investing in knowledge management, countries risk eliminating options in the future due to deteriorating R&D infrastructure or the loss of technology through attrition in the technical ranks (Chapter 2.2.1[C.1]; Chapter 4.4).

5.6. Technology development through international collaboration should be accelerated in multi-recycle and enhanced recycle efforts

Accelerating technology development through international collaboration in multi-recycle and enhanced recycle efforts can lead to great improvements in many aspects of the back end of the fuel cycle. The open-cycle and mono-recycle are established technologies. Multi-recycle and enhanced multi-recycle require further technology development through research, development, and demonstration. These options may offer great improvements in preserving natural resources (Chapter 2.2.2[O.2]), waste characteristics (Chapter 2.2.2[O.3]), and energy independence (Chapter 2.2.2[O.4]). The Generation IV International Forum is one such international collaboration that is working to deploy fast reactors that would facilitate multi-recycle and enhanced multi-recycle options. The development and future deployment of generation IV reactors will require addressing many of the multi-recycle challenges.

5.7. International collaboration should be accelerated in facilitating shared infrastructure in used or spent fuel management to reduce costs

Overall costs are similar for all fuel cycles, but investment in mono- or multi-recycle facilities is required before geological repository construction is necessary. A small number of countries have large and ongoing nuclear power programmes and the infrastructure as well as technical expertise to develop their own back-end strategies. Economies of scale are in their favour. Many more countries with smaller programmes are faced with much costlier solutions relative to the size of their existing programmes (Chapter 3; Chapter 4.3). Sharing infrastructure related to nuclear fuel, in particular reprocessing facilities and deep geological disposal facilities could greatly benefit those countries.

Annex A. Country status

This annex describes in more details the current situation and back-end strategies of each country described Chapter 3.

Belgium

Power reactors

In Belgium, there are seven pressurised light-water reactors (PWRs) dedicated to the industrial production of electricity, located on two different sites: Doel and Tihange. In 2003, Belgium enforced the progressive phase-out of nuclear energy used in industrial energy production law which foresees the end of operation of the Belgian reactors after 40 years of operation. This law has been modified in 2013 and in 2015 to extend the operation of the three oldest reactors by ten years.

Open-cycle

In 1993, the parliament asked the private operator in charge of and hence owner of the nuclear fuel, SYNATOM, to suspend its reprocessing contracts and to not negotiate any new contract without its approval (in total, 670 metric tonne heavy metal [MTHM] was reprocessed). This demand was further confirmed in 1998 when the Belgian government asked the operator to cancel the suspended contracts. Since 1993, Belgium equally considers the open-cycle policy and the mono-recycle fuel cycle. The reference scenario of the owner of the fuel is now the reprocessing for ~25% of the total amount of spent nuclear fuel (SNF) foreseen at the end of operations and the open-cycle for the remaining SNF.

Status of repository development: The Belgian radioactive waste management organisation. In 2011, ONDRAF/NIRAS developed a waste plan in which geological disposal of SNF and High-level radioactive waste (HLW) on a unique site, on Belgian territory, in poorly indurated clay is considered. In its most recent policy proposal (2018), ONDRAF/NIRAS has called for geological disposal of SNF, HLW and medium-level waste on the Belgian territory. A Strategic Environmental Assessment regarding this proposal was submitted to a public consultation in early 2020. This proposal has not yet been translated into a policy. NIRAS/ONDRAF has revised the design of its geological repository in 2017 and a first review of this design by the safety authority is foreseen in the years to come.

Status of SNF extended storage: Temporary storage (on the nuclear power plant [NPP] sites Doel and Tihange) is foreseen until the final repository can accommodate either the SNF or the HLW from mono-recycle. The current planning foresees that the storage will last beyond 2100.

Ownership and responsibilities

The waste that will arise from the nuclear fuel cycle (either SNF as a whole or any other type of waste) will be transferred to the radioactive waste management organisation (ONDRAF/NIRAS) as soon as it is declared as "waste". Nevertheless, the law foresees that the financial responsibility does not end with this transfer and the "producer" of the waste remains liable until the end of the management of its waste. Financial provisions are established under the prudential supervision of a dedicated commission.

Mono-recycle

Mono-recycle is no longer applied to Belgian SNF. Until 1993, 670 MTHM of SNF have been sent to France for reprocessing. The recycle produced 144 mixed oxide (MOX) fuel elements that have been loaded in 2 reactors between 1995 and 2006. The reference scenario of the owner of the fuel in 2019 foresees the additional reprocessing of 10% of the total foreseen amount of SNF.

Multi-recycle and waste minimisation

Although multi-recycle is not considered for Belgium (because of the phase-out of nuclear power), the research on waste minimisation through partitioning and transmutation is supported by the country, mainly through its decision in 2018 to build the MYRRHA research infrastructure.

Rationale

The research on the geological disposal of high-level radioactive waste in clay started as the first nuclear power plants were built, in 1974. Rapidly, Boom Clay was regarded as a potentially suitable host rock for a geological repository and the construction of the underground laboratory for ultra-low level gamma-ray spectrometry (HADES) started in 1980. The same year, the Belgian radioactive waste management organisation was created and, since then has gradually taken over the responsibility for the management and co-ordination of the research and development (R&D) on waste disposal.

Synatom SA, the owner of the SNF from commercial nuclear power plants, manages it using its own resources or allow its management to be carried out by third parties under its responsibility. ONDRAF/NIRAS takes then charge of it in the form of reprocessing waste or as radioactive waste.

Since 2011, the European countries are submitted to the 2011/70 Council Directive. Among others, this Directive establishes the frame for the management of SNF. Belgium has published its first national programme in 2015 which specifies that the reference policy (national policy) for the management of SNF from commercial nuclear power plants is its safe storage of SNF followed by its reprocessing or disposal. ONDRAF/NIRAS will launch a public consultation concerning the geological disposal of radioactive waste and SNF. In the meantime, the country supports the research on waste minimisation through partitioning and transmutation through its decision to build the MYRRHA research infrastructure.

Czech Republic

Power reactors

There are two NPPs under operation in the Czech Republic: Four VVER-440/213 units uprated for 510 MWe in Dukovany site (put into operation between 1985 and 1987), and two VVER-1000/320 units uprated for 1 080 MWe in Temelin site (put into operation 2000 and 2002). In line with the Updated State Energy Policy, approved by the government in May 2015, further use of nuclear energy is envisaged in the energy mix. Details are set out in the National Action Plan for the Development of Nuclear Energy. The Action Plan proposes replacing Dukovany's power output after 2037 with one or two new units, and in Temelin with the construction of the third and fourth units.

Open-cycle

Status of repository development: Site selection for the deep geological repository is scheduled according to a government-approved timetable. Currently, the evaluation of nine candidate sites is being finalised with a proposal to reduce their number to four for more detailed assessment. After its implementation (including the use of the results of the invasive surface survey), two final locations will be selected in 2025 – main and backup. As a host rock, only granite is considered and investigated. The repository is designed to dispose together about

9 900 tonnes of heavy metal and 4 300 tonnes of radioactive waste unacceptable for inclusion in near-surface repositories. There is also an underground research laboratory in which a generic experimental programme has been launched.

Status of SNF extended storage: SNF is stored in interim storages at the sites of power plants. The fuel is stored in dry-type containers, designed for 50 years of service life. There is a backup underground location for a central fuel storage that can be used (in case of new units' construction) to bridge the need for storage from the end of operation of existing units to the opening of the deep repository.

Ownership and responsibilities: The NPP operator is SNF owner and responsible operator of the SNF storages. The state (state organisation SURAO) is owner and operator of the existing repositories and responsible for development and construction of the deep geological repository. Repository operations and the deep geological repository development are covered by a nuclear account, to which the operator of nuclear power plants and radioactive waste producers contribute.

Mono-recycle

There is neither commercial nor research reprocessing facility in the Czech Republic and none is under construction.

Multi-recycle and waste minimisation

The Czech Republic is actively involved in Generation IV reactor research activities on international and national level. Such involvements are: A participation in the ALLEGRO Project (gas-cooled fast reactor demonstrator), newly constructed experimental loops (super critical water loop [SCWL], high temperature helium loop [HTHL], liquid metal Pb-Bi loop), the loop using Pb-17Li for studying of the ITER Fusion Tokamak cooling, or testing of molten salt properties as a Molten salt reactor or fluoride salt-cooled high-temperature reactor coolant. The conceptual design of a small-modular reactor using the molten salt as a primary and secondary coolant, is being developed. However, no commercial radiochemical treatment of irradiated fissile material or spent nuclear fuel is planned in the Czech Republic in the future.

France

Power reactors

The French nuclear fleet has 58 operating PWRs. The Flamanville 3 EPR reactor is under construction with fuel loading scheduled for the end of 2024. According to the French Energy Transition Law for Green Growth that caps the installed nuclear capacity to 63 Gigawatt (electrical) in France, the shutdown of two 900 MWe units in Fessenheim has to take place by the commissioning of Flamanville 3. Thirteen power reactors (two fast reactors, one PWR, one heavy-water gas-cooled reactor and nine gas-cooled reactors) are at various stages of decommissioning.

Open-cycle

France does not currently pursue an open-cycle nor the direct disposal of spent nuclear fuel.

Mono-recycle

The reprocessing of used nuclear fuel (UNF) is a high priority embodied by the development of an industrial know-how. Every year, about 120 MTHM of MOX fuel is produced to be used in the EDF nuclear fleet (24 reactors have the authorisation to use MOX fuel). This fuel is produced by the Melox plant in Marcoule. The plutonium is separated at La Hague plant which reprocesses annually around 1 100 MTHM of UNF to meet the demand for MOX. This level of reprocessing corresponds to UNF discharged annually by the French nuclear reactors in operation. Four reactors are also licensed to recycle reprocessed uranium as enriched reprocessed uranium fuel. The existing industrial facilities already enable a significant improvement in nuclear waste management: fission products and minor actinides are encapsulated in a glass matrix and structural pieces (hulls and end-piece) are also conditioned in standardised canisters suitable for transport, storage and final disposal. The volume reduction of conditioned waste pending final disposal is significant (about five times less than for open-cycle). The final disposal for high-level waste and low- and intermediate-level waste is scheduled to take place in the deep geological repository called the Industrial Center for Geological Storage (Cigéo), for which the application for a licence to construct the complex is in preparation (Cigéo website: www.andra.fr/cigeo/les-documents-de-reference).

Multi-recycle and waste minimisation

The French fuel cycle policy is based on a comprehensive legislative framework. It has been defined by the 1991 Waste Act and the 2006 Planning Act on radioactive and waste materials. The rationale of this policy is based on (i) reducing nuclear waste volume while producing a safe and secure engineered form, (ii) saving uranium resources by enhancing reprocessed materials (U and Pu), and (iii) preparing the future for generation IV (Gen IV) reactors which will strengthen French energy independence and guarantee the sustainability of nuclear energy.

The implementation of this policy follows a stage-by-stage and transparent approach. The 2006 Law is implemented through a national plan for the management of nuclear waste and radioactive materials (PNGMDR), updated every three years. An independent commission, the Commission Nationale d'Evaluation (CNE2), carries out an annual assessment of the research progress for the management of radioactive materials and waste. The French Parliament Science and Technology Committee (OPECST) and the French Safety Authority (Autorité de sûreté nucléaire) are also involved in the decision making and review processes.

The Multiannual Energy Plan (MAEP) for 2019-2023 and 2024-2028 periods

The MAEP aims at completing the transition towards an energy system more efficient and meeting France’s objectives to keep greenhouse gas emission in line with French commitments to the EU and to the Paris Climate Agreement.

The MAEP is a progressive long process and reached a milestone in January 2019 with the release of a draft document which specifies the French government’s orientations:

- Confirmation that the closure of the fuel cycle is of strategic importance for the country.
- The mono-recycle back-end strategy will continue at least until 2040.
- The R&D programme to support the closure of the nuclear fuel cycle will focus on the multi-recycle of UNF in PWRs in the medium run, while maintaining research to prepare the perspective of a potential industrial deployment of a fleet of sodium-cooled fast reactors in the second half of the 21st century.

If the nuclear fleet includes fast reactors, minor actinides transmutation may be considered.

Rationale

The rationale of the French fuel cycle policy is based on:

- reducing nuclear waste volume to be disposed of and producing a safe and secure engineered waste form;
- saving uranium resources by enhancing reuse of materials (U and Pu);
- preparing the future towards Gen IV reactors which will strengthen the French energy independence and guarantee the sustainability of nuclear energy.

Hungary

Power reactors

Currently Paks NPP (Paks I) is the only operating nuclear power plant in Hungary with four VVER-440/213 units uprated for 500 MWe. The units were put into operation between 1982 and 1987. An Inter-Governmental Agreement was signed with Russia for the construction of two new VVER-1200-type nuclear power plant units (Paks II) at the Paks site. These reactors are planned to be commissioned in mid-2020s.

Open-cycle

Status of repository development: The Public Limited Company for Radioactive Waste Management (PURAM) – designated by law – is responsible for the execution of the tasks defined in the national policy and in the national programme. The preparations for the disposal of SNF and high-level radioactive waste in a deep geological repository started in 1995 in the Boda Claystone Formation, in the Mecsek Mountain area. After financial difficulties, a revision of the whole programme became necessary. PURAM developed a new investigation plan, which was approved in 2013. The purpose of the ongoing surface-based exploration is to select the target site and provide its general characterisation. The last phase of the surface-based investigation aims at the site selection of an underground research laboratory.

Status of SNF extended storage: Interim storage of SNF from Paks I takes place in the Spent Fuel Interim Storage Facility in Paks. The storage is a modular vault dry storage type facility, the capacity of the facility has been (and will be) extended as necessary. The interim storage facility has to be kept in operation at least till the final disposal in the domestic deep geological repository is available. During the 50 years of operation of Paks I, 17 716 SNF assemblies (2 126 MTHM) will be produced.

Ownership and responsibilities: The PURAM (government agency) performs the tasks related to the interim storage and final disposal of SNF, it is responsible to site, construct, and operate a geological repository. The reactor owner (the state) is responsible for paying for the cost of storage and disposal.

Mono-recycle

There are no commercial reprocessing facilities in the Hungary and none are under construction.

Multi-recycle and waste minimisation

Hungary is actively involved in international fast reactor research activities. The goal of the ALLEGRO Project is to design, build and operate the first gas-cooled fast reactor demonstrator in the Central European region. The original concept of ALLEGRO was designed in France by the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) with the aim to develop a high temperature fast flux test facility. The ALLEGRO design studies have been shared in the Euratom project since 2005. In 2010, CEA proposed the continuation of the ALLEGRO Project to three institutes from Central Europe: MTA EK (Hungary), ÚJV Řež, a.s. (Czech Republic) and VUJE a.s. (Slovak Republic), later National Centre for Nuclear Research (NCBJ, Poland) joined this activity. The first phase of the project aims to develop the conceptual design of the ALLEGRO reactor and answering all safety related and other technical issues. The corresponding roadmap for the design works and safety analysis is under realisation and the conceptual design has to be completed by 2025. Hungary will host the research activities on advanced fuel, therefore a "fuel institute" will be constructed with the necessary infrastructure.

Japan

Power reactors

After the East Japan Great Earthquake in 2011, all nuclear power reactors were shut down, and it has been decided that some are to be decommissioned. As of July 2019, Japan currently has 36 reactors which are in various stages in the process to restart. Nine of them are operating, and 18 have applied for and under safety review by the Nuclear Regulation Authority. It has been decided to decommission twenty-four reactors.

Open-cycle

Japan's policy is to reprocess UNF, and therefore direct disposal is not planned.

Mono-recycle

As stated in the national "Strategic Energy Plan", which was adopted by the Cabinet in 2018, the basic policy of Japan is to promote a nuclear fuel cycle that reprocesses UNF and effectively utilises the plutonium retrieved, from the viewpoint of effective utilisation of resources and reduction in the volume and harmfulness of HLW.

To date, UNF have been reprocessed domestically at the Rokkasho Reprocessing Plant (RRP, under construction), and the Tokai Reprocessing Plant (designated for decommission). Some 425 MTHM and 1 140 MTHM of UNF have been reprocessed in these two plants respectively. Other from this, 7 100 MTHM of UNF have been sent for reprocessing in the United Kingdom and France.

The RRP is scheduled to start operating in the first half of the 2021 fiscal year, and has a reprocessing capacity of 800 MTHM per year. The plutonium reprocessed here will be fabricated into MOX fuel in the MOX Fuel Fabrication Plant adjacent to the RRP, which is scheduled to operate in the first half of the 2022 fiscal year. Until the RRP starts operating, UNF will be stored in the pools and dry storage facility in each nuclear power plant sites, and an off-site storage site is under construction in Mutsu.

Currently, four reactors are loading MOX fuel, and six more reactors that are planned to load MOX fuel are applying for the regulatory process to restart.

To secure funds for expenses for the steady and efficient reprocessing operation of UNF, the "Spent Nuclear Fuel Reprocessing Fund Act" was promulgated in May 2016, and based on this act the Nuclear Reprocessing Organization of Japan was established in October 2016, with the authorisation of the Minister of Economy, Trade and Industry. The electric power companies are obliged to make annual payments to the implementing body to secure funds for nuclear reprocessing projects.

Multi-recycle and waste minimisation

The government will continue with research and development related to measures for the reprocessing and disposal of used or spent MOX fuel and consider the issue in light of the status of the generation and storage used or spent MOX fuel, trends in reprocessing technologies, and the intentions of relevant municipalities. In terms of waste minimisation, research and development is being undertaken.

The introduction of a fast reactor is pursued, and further research and development will be conducted according to the Strategic Roadmap for fast reactor development.

Rationale

Japan remains committed to this policy from the viewpoint of effective utilisation of resources and reduction of the volume and harmfulness of HLW.

Korea

Power reactors

As of May 2018, 24 nuclear power reactors are in operation with the capacity of 22 529 MWe. Twenty reactors are PWRs and the other four reactors are CANDU (CANada Deutérium Uranium) pressurised heavy-water reactors (PHWRs). Five PWRs are under construction with plans for commercial operation and the last one is supposed to be connected to the electricity grid in 2023. The oldest PWR (Kori-1) was shut down permanently in June 2017. The current government plans to pursue a nuclear phase out policy and hence no reactors are planned to be constructed.

Open-cycle

In Korea, the national policy for the SNF management has not yet been decided. In 2015, the Public Engagement Commission on Spent Nuclear Fuel Management (PECOS) recommended the implementation plan for the spent fuel management to the government after a series of public deliberations, including international seminars and town hall meetings for nearly two years. In 2016, the Ministry of Trade, Industry and Energy (MOTIE) announced a basic plan for HLW management based on the PECOS recommendation.

Status of repository development: Based on the basic plan for HLW management, the government is planning to secure a site for the radioactive waste management facility which includes licensing URL, interim storage and disposal all together. Considering the time required for the site selection including a geological survey, the site is planned to be decided in 2028. The interim storage and disposal facility is planned to be operating in 2035 and 2053, respectively.

Status of SNF extended storage: As of the end of 2017, approximately 16 000 MTHM of SNF was generated in Korea. On this amount, 8 000 MTHM is from PWRs and the other 8 000 MTHM is from PHWRs. Most of the PWR SNF are stored in the on-site water pools. For the PHWR SNF, additional on-site dry storage with the capacity of about 6 000 MTHM is operating due to the saturation of pools. There is still a need to extend the storage somehow until the centralised interim storage is in operation.

Ownership and responsibilities: A Quasi-governmental organisation affiliated with MOTIE, Korea Radioactive Waste Agency (KORAD) is in charge of radioactive waste management including an operation of the nuclear waste management fund which was paid by reactor operator.

Mono-recycle

Mono-recycle option is not considered in Korea due to the non-proliferation issue.

Multi-recycle and waste minimisation

Korea is working on the R&D of the pyroprocessing in combination with the sodium-cooled fast reactor for the minimisation of a repository size and a toxicity of SNF. For the pyroprocessing, Korea is collaborating with the United States through a ten-year long Joint Fuel Cycle Studies (JFCS) till 2020 to check the technical feasibility, economic viability, and non-proliferation acceptability. After the end of the JFCS, Korean government will make a decision whether or not to continue the R&D on the pyroprocessing and the sodium-cooled fast reactor technology.

Russia

Power reactors

Russia has 37 operating nuclear power reactors (thermal reactors: VVER-1000/1200: 15 units; RBMK-1000: 11 units; VVER-440: 5 units; EGP-6: 4 units; Fast reactors: BN-600: 1 unit; BN-800: 1 unit); 6 units VVER-1200 type and 1 floating NPP unit are under construction; 5 nuclear power reactor units are in various stages of decommissioning. The planned layout of future NPPs in the territory of Russia has been set out by the Government Order of the Russian Federation № 1634-r of 1 August 2016. List of nuclear power plants scheduled for construction until 2030 includes 11 new power units.

Open-cycle

Russia is not pursuing an open-cycle and direct disposal of SNF in a geological repository.

Mono-recycle

Centralised UNF management is provided at two sites: PA Mayak and Mining & Chemical Combine (MCC). Industrial-scale UNF reprocessing is performed at RT-1 (PA Mayak). Plant RT-1 at "PO Mayak" has been operating since 1977. At present, about 6 thousand tonnes of SNF have been processed. The design capacity is 400 tonnes per year. At present, the UNF of VVER-440, BN-600 and research reactors and defective fuel of RBMK (which cannot be accommodated in dry storage) are reprocessed at the RT-1 plant, the reprocessing of VVER-1000 UNF has been in place since 2016. For a new reprocessing facility – the Pilot Demonstration Center (PDC) in MCC – reprocessing technologies were developed (based on the Simplified PUREX process) without the discharge of liquid radioactive waste (effluents). The main products of PDC – mixed oxides of plutonium, neptunium and uranium for the manufacture of fast reactor fuel, as well as reprocessed uranium (repU), and HLW immobilisation in borosilicate glass. In 2016, a licence was granted to operate first start-up complex of UNF reprocessing PDC at MCC site. A R&D programme aimed at developing innovative UNF reprocessing technologies was launched in 2016. Construction of the second PDC section with a design capacity of 250 tonnes of UNF per year is now underway. It is scheduled to be completed in 2020.

Reprocessed uranium has been reused in Russian commercial nuclear reactors (RBMK type, BN VVER-440, VVER-1000) since 1996. At present, the Russian fabrication plant MSZ has a licence for reprocessing nuclear materials based on reprocessed uranium with 232-U content up to 5·10-7%. Russia started using MOX-fuel (the first core was a hybrid zone with UOX fuel, MOX fuel – pellet and vibropacking from semi-industrial facilities, and began using MOX fuel fabricated at industrial facility in the MCC in January 2020) in the fast reactor BN-800 (Rosatom website: www.rosatom.ru/en/press-centre/news/the-first-serial-batch-of-mox-fuel-loaded-into-bn-800-fast-reactor-at-beloyarsk-npp).

In 2016, a siting and construction licence was granted for an underground research laboratory in the Nizhnekansk rock massif, which will enable to gain information and experience directly applicable to a future deep geological repository in Russia. In 2024, the commissioning of a URL is expected.

Multi-recycle and waste minimisation

For the sustainable fuel cycles and waste management, Russia has R&D and industrial activities with both thermal and fast reactors. Russia starts using MOX fuel for fast reactor BN-800 for Pu multi-recycle. The reactor design and construction of the on-site closed fuel cycle facilities including dense (U, PU)N fuel fabrication (for BREST-OD-300 lead-cool fast neutron reactor) are expected to be accomplished by 2025.

For repU and Pu multi-recycle in thermal reactor, Rosatom is developing REMIX fuel conception (plutonium with adding enriched repU and natural uranium) with 100% loading in the reactor core.

For ultimate waste minimisation, research into partitioning and transmutation R&D is ongoing.

Rationale

The core principle of the Russian policy in the field of UNF management involves UNF reprocessing to prevent UNF accumulation, to recycle the nuclear material to recover the remaining energy resource of the UNF and to reduce uranium demand, and to ensure the environmentally-friendly management of radioactive waste (fission products and minor actinides). The task of ensuring the safe management of radioactive waste is considered to be, on the one hand, a key element of the national security and safety, and, on the other hand, an essential precondition for present and future use of atomic energy.

The Energy Strategy of the Russian Federation Until 2030, approved by the Russian government, provides for the following efforts in the field of nuclear fuel cycle and nuclear power:

- upgrading NPP capacities with thermal reactors;
- construction of experimental and commercial power plants with fast neutron reactors;
- implementation of a closed nuclear fuel cycle involving new technologies and new enterprises.

The key goal of this policy is to reach the equivalence of the rate of waste accumulation and the rate of waste disposal on the base of advance fuel cycle technologies development.

United States

Power reactors

As of July 2019, the United States has 97 operating nuclear power reactors. Two reactors are under construction with plans for commercial operation. Additional reactors are in various stages of planning. Combined construction and operating licences have been issued and are active (not suspended, cancelled, or terminated) for eight reactors. Seven reactors have completed decommissioning but are storing SNF in independent spent fuel storage installations (ISFSI). Twenty-two reactors are in various stages of decommissioning.

Open-cycle

Status of repository development: The Nuclear Waste Policy Act of 1982 (NWPA) directs the US Department of Energy (DOE) to site, construct, and operate a geological repository for SNF and HLW. The 1987 amendments to the NWPA directed DOE to focus its efforts solely on Yucca Mountain, about 100 miles north-west of Las Vegas, Nevada. The DOE determined in 2002 that Yucca Mountain would be a suitable location for a repository. Later that year, Congress and the President endorsed that decision through the enactment of a joint resolution approving the site. A licence application for a geological repository at Yucca Mountain, Nevada is pending at the US Nuclear Regulatory commission (NRC).

Status of SNF extended storage: Most of the US nuclear power plants are storing SNF in NRC-licensed ISFSIs located on-site. As of the end of 2019, the US nuclear power industry had generated more than 80 000 MTHM of SNF, currently stored at 80 sites. Of this amount, 27 000 MTHM is in dry storage at nuclear power plant sites. Most permanently shut down commercial reactors currently have, or are planning to have, their SNF stored at on-site ISFSIs pending disposal. There has been commercial interest in consolidated interim storage, with two applications under review at the NRC.

Ownership and responsibilities: The US government is responsible to site, construct, and operate a geological repository. The reactor owners are responsible for paying for the cost of disposal.

Mono-recycle

There are no commercial reprocessing facilities in the United States and none are under construction. Nuclear Fuel Services operated the only commercial reprocessing facility in the United States at West Valley, New York, from 1966 to 1972.

Multi-recycle and waste minimisation

The United States recognises that R&D of sustainable fuel cycles and waste management activities are important to support the expansion of nuclear energy. The research focuses on sustainable fuel cycle options and technologies that have the potential to improve resource utilisation and energy generation, reduce waste generation, enhance safety, and limit proliferation risk. Research on advanced and innovative analytical technologies, characterisation technologies and online monitoring tools to support the back end of the nuclear fuel cycle will strengthen the sustainability of advanced nuclear fuel cycles.

Rationale

US policy on radioactive waste disposal, including SNF and HLW, has been informed as early as the 1950s by a consensus among scientists that radioactive waste can be disposed of safely in a variety of ways at a large number of sites in the United States. Additionally, spent nuclear fuel can be disposed of safely by deep geological disposal and the United States has a variety of sites with a variety of geological media that may be suitable for this purpose. Regarding reprocessing, the United States briefly deferred the pursuit of reprocessing commercial used nuclear fuel in the 1970s over proliferation concerns. That policy was later reversed but commercial reprocessing has never been pursued by private industry. The US government continues to invest limited resources into research and development on reprocessing technologies focused on cost reduction, waste management resulting from reprocessing, and material protection, accountancy, and control technologies related to reducing proliferation risk. However, there is no compelling need within the United States at this time to increase that investment or offer incentives to private industry to pursue commercial reprocessing.

Annex B. Economic impact in La Hague

The implementation of fuel cycle options leads to new socio-economic opportunities. Reprocessing and mixed oxide (MOX) fuel fabrication plants can be built on the same site or on different sites. For instance, in France the reprocessing plant in La Hague accounts for around 5 000 direct jobs in western part of France and the Melox MOX fuel fabrication plant, located in the South of France, directly employs 800 people.

In the United States, a prospective regional impact study for an 800 t/year reprocessing pilot plan indicated that 16 000 direct and indirect jobs could be created during the operational phase. During the construction phase, the facility could lead to the creation of up to 42 000 direct and indirect jobs. Overall the employment multiplier compared to a consolidated interim storage facility would be around 3.

Reprocessing plant impact on population: La Hague case

The Orano site “La Hague” was implanted more than 40 years ago in the Manche department at Cap La Hague. In this isolated peninsula, the main activity was farming with numerous small holdings. Fishing was often a complementary resource for local farmers.

The building, then the operation of the reprocessing plant brought some profound changes: around 5 000 people are working today in the facility which has generated more than 10 000 indirect jobs. From 1962 to 2010 the population around the facility grew from 24 000 to 43 000, a 75% growth ratio to be compared to the 35% average growth in France for the same period.

The socio-professional structure has also been changed markedly: the number of farmers decreased while at the same time the number of technicians, engineers, executives and office workers rapidly increased. The newcomers, younger, and with a higher level of education have been easily integrated with the local ageing population.

Economic impact

The La Hague facility is an important local taxpayer, with approximately EUR 80 million of taxes paid in 2016. It is also a large local contractor in the region: EUR 525 million of external purchases were made in 2016, among which more than 70% with suppliers of the Normandy region. On average, EUR 200 million of yearly investments are made, from which EUR 100 million are dedicated to the long-term operation and safety of the facilities. These regional purchases have had a big impact on the development of the local industrial sector: 170 companies developed a specialisation in the activities of the nuclear cycle, among which are 120 small and medium-sized enterprises (SMEs). These specialised SMEs are very dynamic, actively recruiting and exporting: the annual staff growth rate is of about 7% in recent years, when much of the French industrial sector is laying off workers.

The needs for the construction and for the operation of the La Hague plant boosted the development of the heavy infrastructure of the region, which benefited local development in a number of areas. Improvements to the telecommunication and road networks, electrical grid as well as port facilities, have all been noted.

Other economic impact: Research and development aspects

For supporting the industrial development and operation, high-level research and development (R&D) is necessary. Concerning back-end aspects, mono-recycle and multi-recycle both demand increased capacity with regards to open-cycle. Currently R&D for mono-recycle in France directly employs several hundred people. For multi-recycle, additional R&D devoted to generation IV reactors and fuel has to be undertaken. For the front-end, the R&D needs are approximately the same whatever the chosen cycle.

Annex C. Shared infrastructure, international co-operation on used or spent fuel management

Almost from the start of nuclear power industry, international co-operation took place. Early initiatives from the 1950s led to the International Atomic Energy Agency (IAEA) statute, initial focus of international collaboration was on the front end of the nuclear fuel cycle, back-end issues to be taken up at a later stage.

Today, more than 50 countries have used or spent nuclear fuel (UNF or SNF) from commercial nuclear power plant (NPP) and research reactors stored currently in temporary sites, awaiting reprocessing or disposal, amounting to hundreds of thousands of tonnes. The subject of UNF or SNF and radioactive waste management influences both the economics and the public acceptance of nuclear power, the future management of UNF or SNF and radioactive waste is a fundamental for the sustainability of nuclear power and its potential expansion.

Under the Joint Convention on the Safety of Spent Fuel and of Radioactive Waste Management, contracting parties have agreed that the country discharging SNF and receiving the benefits of the power generated bears the responsibility for its management, including disposal.

Building a national deep geological repository (DGR) is a tremendously difficult challenge for many countries, and accordingly, a multilateral approach to the back end of nuclear fuel cycle has been regarded as an attractive option. Some countries may not have the right geology to dispose of waste underground. In addition, for many countries with existing small nuclear programmes or new nuclear power programmes, the costs of a DGR are prohibitive. There may be considerable advantages in cost, safety, security and non-proliferation gained from international co-operation in the back end of the nuclear fuel cycle. If SNF and/or High-level radioactive waste (HLW) can be collectively reprocessed or stored and disposed in multinational infrastructures to be intensively monitored and well protected, security and safety concerns about nuclear materials can largely be reduced. The current situation in a number of countries, in which SNF is stored at scattered reactor site facilities for extended period of time pending future decision, may induce more vulnerability to external shocks such as the growing risk of natural disasters and terrorist attacks.

Both the Joint Convention and the EC 2011 directive on SNF and radioactive waste management state that in certain circumstances, safe and efficient management of SNF and radioactive waste might be fostered through agreement among countries to use facilities in one of them for the benefit of the others. Although the final responsibility for the management of radioactive waste lies with each member country, two or more member countries can agree to share a final repository located in one of them.

Technically and economically, the potential benefits of multinational facilities are broadly recognised, but their implementation depends on the political will of the participating countries. It should be noted that, except for UNF reprocessing, such political will has yet to manifest.

The initial phase of multinational co-operation focused on recycle strategies and minimising nuclear fuel cycle infrastructure among interested partners, which lead to shared investment in recycling facilities in France and in the United Kingdom at the end of the 1980s. Reprocessing of significant amount of UNF has been largely and successfully implemented on a multinational basis, demonstrating the feasibility of this approach for the back end of the fuel cycle.

The possibility to have reprocessing carried out abroad is a first step towards multilateral co-operation on the back end of the fuel cycle. Today, this is an available strategy choice for any country with a nuclear power programme, since there is a commercial market providing reprocessing services. This service is currently offered by France and Russia. International co-operation is therefore already in place for UNF reprocessing or recycling. However, there are currently no service providers offering a full back-end solution, i.e. accepting UNF without any return of HLW. The incentives today are to be able to move UNF off-site even after a period of interim storage and to receive final waste back several years later. Return of waste is carried out in universal canisters, an assured quality made of a vitrified stable form specifically designed for confining, much smaller in volume than the SNF. The benefits include the building of storage facilities, lower storage and disposal volumes for HLW than for SNF. A significant positive aspect is that the highly active glass canister, in contrast to spent fuel, does not fall under IAEA safeguards nor present a proliferation risk. HLW universal canisters specifically designed for the storage, transport and disposal purposes are currently licensed by many safety authorities. These specific characteristics of the final waste form would facilitate the disposal of HLW canisters in a shared geological disposal in comparison with SNF.

Given the delay in demonstrating and implementing DGRs, the probability that SNF will be have to be stored for many decades is high. Additionally, the increasing recognition that SNF might be a valuable resource in the future could emphasise extended period of interim storage. Centralised interim storage specially to consolidate spent fuel stored at stranded sites is seen as a mean to optimise resources and security management. Multilateral interim storage infrastructures could become an option if nuclear power continues to expand. However, the incentive for countries to develop multinational storage facilities may not be seen as high, unless it is associated with future multinational disposal.

There is a long history of shared disposal initiatives since the 1970s, so far all have failed for political, technical and/or economic reasons. Over the past decade there has been an increasing interest in the concept of multinational or regional disposal with numerous ongoing studies (Nuclear Threat Initiative [NTI], European Repository Development Organisation [ERDO], Arius, International Framework for Nuclear Energy Cooperation [IFNEC], etc.) being undertaken with support from the EC, IAEA, and the NEA.

However, the issue of importing radioactive waste remains very sensitive, and is even forbidden by law in several countries. The 2011 EC directive allows that EU members may join a disposal facility, but limits export of EU radioactive waste beyond its borders under very specific conditions.

Being a partner in a collaborative repository development project does not remove the requirement that each country should have a national policy and strategy. The advantages and disadvantages of including the option of multinational repositories within the national strategy will vary from country to country depending, among other parameters, on the scope of the domestic nuclear programme, national technological capabilities, national institutional framework, economic conditions, public acceptance of waste repositories and geographical location. An attractive approach is to keep the option of multinational co-operation open, while actively developing and implementing a national strategy for radioactive waste management and national skills in this area. This dual track approach should be followed until either a national or a multinational solution has been implemented.

There is significant ongoing multinational co-operation in several areas in the back end of the nuclear fuel cycle. However, there has been very limited co-operation on implementing radioactive waste disposal. Indeed, co-operation between waste management organisations in different countries is well established but limited to the area of research and development.

Such a large-scale multinational project, highly technical in nature and demanding innovative investment, extending over several decades, is politically and socially sensitive. Technical, financial, institutional, and socio-political issues will have to be overcome. There are almost no challenges faced by multinational disposal initiatives that are not also faced by national disposal programmes in democratic countries. The technical and economic challenges may in fact be more easily addressed by several partners than by a single nation. Nevertheless, the uncertainties are principally of a socio-political nature and are undoubtedly greater in multinational projects.

Progress towards the establishment of geological repositories in most countries with nuclear power has been slow and as no deep geological repository is yet in operation it can be argued that the safety and technical durability of these facilities has still to be demonstrated. A geological repository is also a very long term, well beyond a century, and complex project in terms of social, technical, scientific, and institutional challenges, to be addressed by a country for the first time. Multinational repository development will depend on the progress made with national repositories.

Different scenarios for implementing multinational repositories have been developed. Three major possibilities were identified: "add-on" (a large programme accepts waste from smaller ones), a "supranational concept" in which a facility with truly international management and control is implemented, and "partnering scenarios" in which countries collaborate in a multinational repository.

Co-operation among geographically contiguous or close states to develop shared regional disposal facility projects may be the most credible approach. The more promising development may be for countries with small or new nuclear power programmes to collaborate with similar countries in efforts to implement shared, multinational repositories.

A multinational repository could offer substantial benefits to the countries involved. One of the main benefits is in the economic advantages accruing from a combined disposal operation. A geological repository is an expensive undertaking with high fixed costs (siting, characterisation, licensing and initial construction) that are largely independent from the size of the repository. The high fixed costs result in economies of scale that favour repositories with capacities for large quantities of SNF and HLW. In addition, shared repository may lead to a potential enhancement of global nuclear safety and security. Resource sharing, in research and development expertise, technical problem solving capability, repository siting experience and facility design know-how are other benefits.

Finally, the level of complexity of such a project is probably very different when considering shared repositories of HLW universal canister following reprocessing of UNF alleviating many challenges compared to shared SNF direct disposal option. This could be reached through multinational collaboration all along the back end of the fuel cycle, part of which is already available.

Annex D. **Managing safety**

Any significant changes to the business process structure, functional structure, or organisational structure caused by the application of new back-end options requires increased attention to safety issues.

Under the 2016 IAEA safety standards which introduced the concept of "Leadership and Management for Safety", the human factor, instead being seen as a source of danger, was transformed into a key instrument for ensuring safety in the related changes in national nuclear energy programmes, including the implementation of new options in nuclear back end. This concept requires a specific Executive structure ("an Integrated Management System"), which should facilitate the formation of safety culture as a unique culture of the organisation, which is established in the course of solving the organisation's problems of safety in the circumstances of significant changes in its activity. IAEA guidance documents on the practical implementation of this new concept are under development.

The concept will reorient nuclear power plant (NPP) specialists to the advanced solution of the known and potential problems of NPP operation, including the ability to identify and formulate problems of NPP operation and mastering the skills of project management in solving problems at their workplace. At the same time, the operating organisation will create an integrated management system that provides:

- Prompt consideration and analysis of the identified problems by using communication network and identification of leaders who can find a solution to the problem.
- Formation of teams led by senior managements for pilot problem solving and rapid implementation of the results through organisational learning.
- Creation of conditions to privilege the formation of a "culture of partnership" in addition to the traditional "culture of power" or "culture of role" established at operating nuclear power plants.

As a result, the operating organisation will create an integrated management system based on knowledge, key elements of which will be: building a community of practice, working in a network mode and providing an operational solution to the challenges of NPP operation and the implementation of innovations.

The challenge is that the creation of an integrated management system and the formation of a unique organisational culture will have to take place while solving problems in such a complex area as the nuclear fuel back-end.

Summary

Under the 2016 IAEA safety standards which introduced the concept of "Leadership and Management for Safety", the human factor, instead being seen as a source of danger, was transformed into a key instrument for ensuring safety in the implementation of new options in nuclear back end and the related changes in national nuclear energy programmes.

Managing safety is more of a common issue for all options and no significant differences exist among the different options. The required level of safety must be achieved in each fuel cycle option.

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Strategies and Considerations for the Back End of the Fuel Cycle

A wealth of technical information exists on nuclear fuel cycle options – combinations of nuclear fuel types, reactor types, used or spent nuclear fuel (SNF) treatments, and disposal schemes – and most countries with active nuclear power programmes conduct some level of research and development on advanced nuclear fuel cycles. However, perhaps because of the number of options that exist, it is often difficult for policy makers to understand the nature and magnitude of the differences between the various options.

This report explores the fuel cycle options and the differentiating characteristics of these options. It also describes the driving factors for decisions related to both the development of the fuel cycle and the characteristics resulting from implementing the option. It includes information on the current status and future plans for power reactors, reprocessing facilities, disposal facilities, and the status of research and development activities in several countries. It is designed for policy makers to understand the differences among the fuel cycle options in a way that is concise, understandable, and based on the existing technologies, while keeping technical discussions to a minimum.

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