NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

(2018 update)

Watching brief on advanced fuel cycles

The Nuclear Waste Management Organization (NWMO) developed the Adaptive Phased Management (APM) approach after an extensive study and engagement with Canadians coast-to-coast during 2002 to 2005 to identify a long-term management approach for Canada's used nuclear fuel. In considering different methods of managing used nuclear fuel for the long term, Canadians clearly identified their values and priorities as:

- Safety and security must be our top prioritiy;
- This generation must take responsibility for the waste it has created;
- We must use best international practice; and
- We must have flexibility for future generations to make their own decisions.

The APM approach best meets these values and priorities. It was selected by the Government of Canada in 2007 as Canada's plan. The technical end point of APM requires used nuclear fuel to be safely contained and isolated in a deep geological formation where it can be monitored, and if need be, retrieved. This is consistent with the policy direction of all countries with major nuclear power programs – even countries that currently practice or advocate various forms of recycling are planning to construct deep geological repositories to manage the resulting wastes.

During the national study, Canadians expressed interest in knowing more about the possibility of recycling or reusing used nuclear fuel. The NWMO's analysis concluded that reprocessing of used fuel was a highly unlikely scenario for Canada at that time. However, the NWMO recommended keeping a watching brief on the status of the technology internationally, and the potential for change in the fuel cycle in Canada.

The NWMO has been maintaining and regularly publishing watching briefs. This edition of the watching brief paper outlines recent international research and developments in nuclear fuel cycles, and discusses their potential applicability to Canada, as well as the time frames by which any new fuel cycle could be introduced in Canada. The main conclusions are:

- Advanced fuel cycles are not likely to be implemented in Canada on a commercial scale in the near future.
- The introduction of small modular reactors (SMRs) in Canada would result in new used fuel waste types that will need to be managed. The impact of these potential new wastes on the NWMO program will need to be evaluated as part of the consideration of the SMR technologies.
- Waste arising from advanced fuel cycles would be managed by the NWMO in a manner that is safe, socially acceptable, technically sound, environmentally responsible, and economically feasible.
- The NWMO will continue maintaining its watching brief on advanced fuel cycle developments that could have an impact on Canada's future waste management requirements.

Introduction

The NWMO maintains a watching brief on worldwide developments in advanced fuel cycles, including reprocessing and recycling technologies. Previous detailed technical reports [Jackson, 2008, 2009, 2010] and summary watching brief reports [NWMO, 2011, 2012, 2013, 2015a, 2016, 2017a] are available on the NWMO website.

Research and development work continued in 2018 in various countries and international collaborative programs to assess the technology and implications of advanced fuel cycles, including closed fuel cycles based on reprocessing, partitioning and transmutation (RP&T). Findings were presented at a number of international conferences and technical meetings.

This present report focuses on the current status and provides a summary of recent international activities since the 2017 watching brief was published.

Discussion

There are three basic nuclear fuel cycles:

- “Open” or “once through,” in which the fuel is irradiated in the reactor, then considered to be waste when it is removed;
- “Partial recycle” or “twice through,” in which the used fuel is reprocessed to recover plutonium and the remaining fissile uranium, converted to mixed Pu-U oxide (MOX) fuel and reused once in current reactor types, or used fuel from one reactor type is used as fuel in another reactor type with a lower uranium enrichment requirement (i.e., light water reactor (LWR) used fuel is reused in CANDU reactors); and
- “Closed” or “full recycle,” in which the used fuel is reprocessed to recover plutonium and other actinides, then used in advanced reactors such as fast neutron reactors (FRs). The FR used fuel is then reprocessed and continuously recycled in the FRs to extract additional energy. Depending on the configuration of the reactor, additional amounts of natural or depleted uranium or reprocessed used fuel can be added to replenish the fuel consumed in the FR. Other advanced reactor designs, such as molten salt reactors can also be used in closed fuel cycles.

Other variations can include different combinations of reactors, such as a two-tier (or “double strata”) cycle, including combinations of conventional reactors (with or without MOX fuel), advanced reactors and/or accelerator-driven systems (ADSs).

As shown in Table 1, Canada, as well as most other nuclear power generating countries, currently follows the open fuel cycle. A few countries, such as Belgium, Germany, France, Japan, Netherlands, and Switzerland, use or have used partial recycling, with the used MOX fuel either stored as waste, or awaiting future recycling in unspecified future advanced reactors. Recycled uranium from LWRs can be used as new fuel for heavy water reactors (HWRs, e.g., CANDU) in countries that operate both LWRs and HWRs, such as in China. Once it has been reused in the HWR reactor, the used “natural uranium equivalent” (NUE) fuel is considered to be waste. Currently, only China, India and South Korea operate both LWRs and HWRs. A summary of global reprocessing capacity for commercial fuels is shown in Table 2. This summary does not include facilities that operate, or have operated, solely for military purposes.

Table 1: Summary of current status of reprocessing for the nuclear power fuel cycle

Country	Commercial scale reprocessing facility		Currently send used fuel for reprocessing in other country	Some used fuel reprocessed in past	Planning direct placement of used fuel in a repository
	Existing	Planned			
Belgium				✓	✓
Canada					✓
China(3)		✓			✓ (4)
Czech Republic				✓ (7)	✓
Finland				✓ (7)	✓
France(3)	✓ (2)				
Germany				✓	✓
Hungary				✓ (7)	✓
India(3)	✓				
Japan		✓ (6)	✓		
Korea, Rep. of					✓
Mexico					✓
Netherlands			✓ (5)		
Pakistan(3)					
Romania					✓
Russian Federation (3)	✓				
Slovakia				✓ (7)	✓
Slovenia					✓
Spain					✓
Sweden				✓	✓
Switzerland				✓	✓
United Kingdom(3)	✓ (1)			✓	✓
Ukraine				✓ (7)	✓
United States(3)				✓	✓

(1) The United Kingdom will cease all reprocessing at end of current contracts by 2020. The first facility was shut down for decommissioning in 2018.
(2) France supplies commercial reprocessing services to a number of European and Asian countries.
(3) China, France, the United Kingdom, Russian Federation, the United States, Pakistan, and India currently reprocess, or have reprocessed in the past, for military reasons, as well as for nuclear power plant purposes.
(4) China plans direct placement of its used CANDU fuel in a repository. Some LWR fuel is planned to be reused in its CANDU reactors.
(5) Used fuel sent to France for reprocessing. Original contract was for 350 metric tonnes of heavy metal. Contract extended in 2015 to end of life for current reactors.
(6) Commercial scale facility at Rokkasho-mura has been constructed and is undergoing test operation (currently planned to start commercial operation in 2021), but policy currently under review.
(7) Some used fuel was sent to former Soviet Union for reprocessing. Practice terminated in early 1990s.

Table 2: Summary of global reprocessing capacity for commercial fuels

Country	Facility	Capacity (tonnes per year)	Status
China	Gansu	200	Under construction (expected ~2030)
France	UP1, Marcoule UP2-400, La Hague UP2-800, La Hague UP3, La Hague	600 400 800 800	Shut down/decommissioning Shut down/decommissioning In operation In operation
India	(4 facilities)	~330 (total)	In operation
Japan	Tokai Rokkasho	90 800	Shut down/decommissioning In commissioning (expected ~2021)
Russian Federation	RT-1, Mayak MCC, Zheleznogorsk RT-2, Zheleznogorsk	400 60 700 + 800	In operation (expected shut down 2030) In operation Under construction (expected ~2020)
United Kingdom	MAGNOX, Sellafield THORP, Sellafield	1500 900	In operation (expected shut down 2020) Shut down 2018
United States	West Valley	300	Operated 1966-72, decommissioned

While some of the advanced fuel cycles are theoretically sustainable once they reach equilibrium, there are still many scientific and engineering challenges (such as development of suitable materials of construction for the harsh conditions present in the advanced reactors, and the scale up of lab-sized processes to full-sized), as well as socio-political and economic challenges, which must be solved before they can be implemented on an industrial scale.

Beyond the primary benefit of energy security with these systems, a secondary benefit of an advanced fuel cycle is that it may reduce the amount of actinides in the waste and/or demand for space in a high-level waste repository. However, reducing the actinides may not avoid the need for long-term waste management, and any space benefit can only be realized if the separated fission product wastes are stored for several hundred years at surface prior to placement in a repository to allow the decay heat to dissipate. Otherwise, there is no significant benefit to the size or safety of a deep geological repository for high-level waste and used fuel when these additional wastes are included. Indeed, a 2013 comprehensive review of used fuel management options for Korea: "*…no technical justification exists for P&T to be considered an alternative to direct geological disposal, and indeed, no evidence that any of the conventional P&T schemes could, even if they could be implemented, remove the need for deep geological disposal or even make disposal significantly easier or safer*" [MIIS, 2013].

In the United States, after the decision to stop the Yucca Mountain repository licence application, the Blue Ribbon Commission on America's Nuclear Future (BRC) conducted in 2010 and 2011 an extensive review of available options and technologies for management of the back end of the nuclear fuel cycle in the United States. In its final report [U.S. BRC, 2012], the BRC stated that "*…disposal is needed and that deep geologic disposal is the scientifically preferred approach has been reached by every expert panel that has looked at the issue and by every other country that is pursuing a nuclear waste management program.*" The United States Department of Energy announced in 2013 its strategy for management and disposal of spent fuel, based on the BRC report, which starts with operation of pilot interim storage facility, followed by operation of a larger interim storage facility, and includes the consideration of geological disposal [U.S. DOE, 2013]. No progress has been made to date with respect to the final disposal of the spent fuel.

Similarly, the Australian Royal Commission into the Nuclear Fuel Cycle stated that "*there is international consensus that deep geological disposal is the best available approach to long-term disposal of used fuel*" [Government of South Australia, 2016].

Research on advanced fuel cycles is ongoing internationally. Findings were presented at a number of recent international conferences and technical meetings, including:

- 8th International SMR & Advanced Reactor Summit 2018 (March 2018, Atlanta, United States) [NEI, 2018];
- Annual World Nuclear Fuel Cycle Conference (April 2018, Madrid, Spain) [WNA, 2018];
- American Nuclear Society's International Congress on Advances in Nuclear Power Plants, ICAPP 2018 (April 2018, Charlotte, United States) [ICAPP, 2018];
- 20th International Conference on Emerging Nuclear Energy Systems, ICENES 2018 (June 2018, San Francisco, United States) [ICENES, 2018];
- 15th INPRO Dialogue Forum on Sustainable Supply Chain for Advanced Nuclear Power Systems (July 2018, Vienna, Austria) [INPRO, 2018];
- 26th International Conference on Nuclear Engineering, ICONE 2018 (July 2018, London, United Kingdom) [ICONE, 2018];
- Organisation for Economic Co-operation and Development Nuclear Energy Agency's (OECD NEA) 15th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (October 2018, Manchester, United Kingdom) [OECD/NEA, 2018a];
- Pacific Basin Nuclear Conference – 2018 PBNC (September 2018, San Francisco, United States) [ANS, 2018];
- European Nuclear Society's TOPFUEL 2018 (September 2018, Prague, Czech Republic) [ENS, 2018];
- The Nuclear Materials Conference (October 2018, Seattle, United States) [NUMAT, 2018];
- 4th GIF Symposium 2018 (October 2018, Paris, France) [GIF, 2018a]; and
- Canadian Nuclear Society's 1st Conference on Generation IV and Small Reactors (November 2018, Ottawa) [CNS, 2018].

Papers presented at these conferences, as well as technical reports published by the OECD NEA [e.g., OECD/NEA, 2011-2018], International Atomic Energy Agency (IAEA) [e.g., IAEA, 2012-2018], French Commissariat à l'énergie atomique et aux énergies alternatives (CEA) [e.g., CEA, 2015], United States Nuclear Regulatory Commission [U.S. NRC, 2012], Electric Power Research Institute [e.g., EPRI, 2015-2017], the United Kingdom Radioactive Waste Management agency [RWM, 2017], and various international collaborative projects (such as the European Sustainable Nuclear Energy Technology Platform [SNETP, 2012-2018], and Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution [ASGARD, 2016] projects) were reviewed and monitored by the NWMO as part of maintaining this watching brief.

These conferences showed that there is continued interest internationally in advanced fuel cycles, and that progress is being made in the science and technology underlying RP&T and advanced fuel cycles.

NWMO staff have also prepared technical reports and related conference papers outlining the potential impacts of advanced fuel cycles on used fuel inventories and long-term management needs [Gobien, 2016; Ion, 2016; NWMO, 2015b,c].

Some of the potential advanced fuel cycle concepts and options are discussed below.

While there are a few experimental or demonstration FRs in operation or under construction in China, India, and Russia, all the commercial nuclear power reactors in operation or under construction around the world today are based on thermal neutrons. These reactors currently use moderator materials to slow down the high energy neutrons from the fission reactions, and use normal or light water (most non-CANDU reactors), heavy water (CANDU reactors) and graphite (gas cooled reactors). The fuels used in these reactors contain either natural uranium (0.7 per cent U-235, the rest being U-238) such as in the CANDU reactors, or fuel with a higher concentration of U-235 (typically 3 to 5 per cent). Producing this higher concentration is known as enrichment. Operation of current reactor types requires a continuous supply of fresh uranium as a source of the fissile U-235. A byproduct of the enrichment process is depleted uranium, which has a reduced U-235 content of around 0.3 per cent and is now generally considered to be a waste by countries that operate enrichment facilities. However, as noted below, the depleted uranium from the enrichment process is a potential fuel source for some advanced reactor fuel cycles.

There are two main technical reasons why an advanced fuel cycle could be implemented:

- To improve national energy security (e.g., to recover additional energy from the used nuclear fuel and reduce reliance on the need for fresh uranium); and/or
- To reduce burden on a deep geological repository (e.g., to allow the waste from more nuclear-generated energy to be placed in a repository of a given size, or to reduce the radioactivity of the waste in the repository).

The first reason is based on the premise that uranium is too scarce or costly to just use in a once-through fuel cycle, or that indigenous supplies are limited and that access to foreign supplies is unreliable. The second is based on the premise that suitable repository space to manage the resulting wastes will be scarce. Both reasons also assume that nuclear energy continues to be an economic choice for a given country.

It is noted that although recycling of used fuel into FRs may reduce the volume of high-level waste produced per megawatt of electricity generated, it does not always significantly reduce the required footprint area of a repository. This is because the footprint is governed by the total thermal output of the waste, not by its total volume, and the thermal output of the wastes are primarily driven by how much power has been produced regardless of the fuel cycle. Only in the case of very advanced fuel cycles, with full partitioning and transmutation of all actinides maintained over long periods of time, is there any significant reduction in high-level waste repository space requirements. Even in these extreme cases, the reduction in high-level waste repository space is somewhat offset by the large increase in the long-lived intermediate-level wastes resulting from these fuel cycles (which also requires long-term management in a deep repository).

A third reason is also sometimes quoted: partitioning and transmutation will reduce the “radiotoxicity” of the waste by transmuting the transuranic elements. However, while transmutation can eliminate the longer-lived transuranic elements in the used fuel, it does not improve the overall safety of a repository because the transuranic elements have very low mobility in the natural environment and do not migrate from the repository to the biosphere. The very long-lived mobile fission products, such as I-129 (which are not eliminated by the advanced fuel cycles), are generally the key radionuclides for long-term repository safety assessments [Kessler et al., 2012; Sandia, 2012; EASAC, 2014; NWMO, 2017b].

In any event, fully implementing RP&T requires the commercial scale deployment of advanced systems, such as FRs as shown in Figure 1, or ADSs, as well as their associated infrastructure such as reprocessing plants and fuel fabrication facilities. Although FRs have been in existence since the 1950s, they have yet to achieve widespread commercial acceptance and deployment. See, for example, [IAEA, 2012, 2013b] for descriptions of various FR prototypes and their operating histories.

FRs do not use a moderator. They can be used to extract the energy from the U-238, as well as other actinides that are created in a reactor (such as various isotopes of plutonium, americium, neptunium, etc.). In the case of U-238, this is done by first converting the U-238 to Pu-239 via neutron capture and subsequent radioactive decay, and then inducing fission in the Pu-239 by another neutron. As the U-238 is consumed, makeup uranium or other actinides can be added, either from reprocessed thermal reactor fuel or from the depleted uranium from enrichment processes. The use of depleted uranium is generally considered to be the better option, since it is widely available, has very low specific radioactivity and can be more easily handled, whereas the reprocessed uranium and other actinides tend to be very radioactive as a result of the buildup of more radioactive isotopes (e.g., gamma emitting daughter products of the U-232 decay chain).

Current advanced reactor concepts operate at very high temperatures (typically 400°C or more) and use liquid metals (e.g., sodium or lead), molten salts (e.g., sodium fluoride mixtures), or gases (e.g., helium) as coolants rather than water or heavy water. There are a number of prototypes and/or designs that are being promoted by various countries as part of the international GEN-IV collaborative project and by several commercial enterprises. The details of these designs are described elsewhere, such as [IAEA, 2018b, 2018c], [GIF, 2018b].

While some of the designs have the potential to reuse the separated fissile and fertile materials from current used nuclear fuels to extract additional energy, the high temperatures and neutron fluxes combined with the corrosive liquid metal or salt coolants create very harsh conditions for any reactor materials. Investigation of materials that can withstand these conditions for several decades of reactor operation is one of the ongoing areas of research.

Depending on the details of the design, the FR systems can operate in three modes:

- **Burner**, where the reactor consumes more fissile material (i.e., actinides) than it produces. Note that this is the only mode that can eventually eliminate the actinides from current inventories of used nuclear fuel;
- **Self-sustaining or break-even**, where the reactor is in equilibrium and consumes all the fissile material that it produces; and
- **Breeder**, where the reactor produces more fissile material than it consumes (this supplies more fuel for an ever-expanding nuclear program).

All three modes of operation require an initial core loading of highly enriched U-235 or Pu-239 to start up the reactor. The U-235 would be obtained from enrichment of fresh uranium to much higher levels than is currently used for commercial nuclear power reactors (i.e., greater than 20 per cent U-235 versus 3 to 5 per cent for LWRs). The Pu-239 would be obtained from the reprocessing and partitioning of current LWR used fuel. Current reprocessing capabilities around the world are summarized in Table 2. Once started, the reactor can create its own fissile material in situ from U-238 and other actinides in the fuel.

Some reactor concepts, such as many of the molten salt designs, require a makeup supply of fresh slightly enriched to highly enriched fuel to operate, which make them unsuitable to work with used CANDU fuel directly (although they may be suitable for used LWR fuel). In this instance, used CANDU fuel would require blending with enriched uranium in order to create the correct fuel mixture of at least about 2 per cent enrichment. Many molten salt designs also use liquid fuels (e.g., fluoride salts), rather than the solid fuels used in current reactors. Designers claim that these types of fuel systems offer advantages over solid fuels, such as better reactivity control, deeper "burning" of actinides and preventing "meltdowns" (since the fuel is already in liquid form). However, the liquid fuel cycle tends to be much more complex and is not yet fully developed, and even designs with extensive previous analysis (e.g., the Oak Ridge National Laboratory's Molten Salt Breeder Reactor) have not resolved some associated fuel cycle uncertainties [EPRI, 2017].

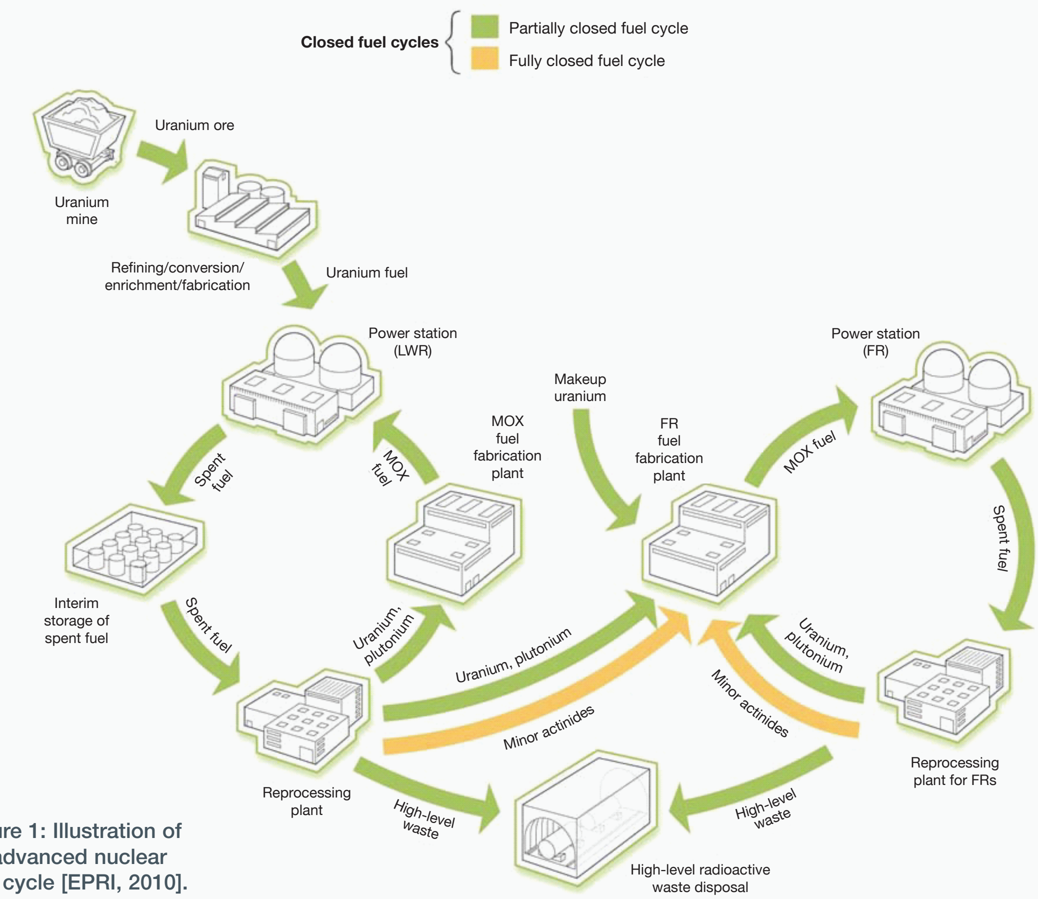

Figure 1: Illustration of an advanced nuclear fuel cycle [EPRI, 2010].

Cost is also an important consideration. In order to be successfully deployed on a commercial basis, the life cycle cost of producing electricity with advanced reactors and fuel cycles must be lower than for other production methods, including current nuclear power plants and non-nuclear technologies. A study published in 2013 by the OECD NEA [OECD/NEA, 2013a] looked at life cycle costs for various fuel cycle options and concluded that the once-through fuel cycle was the least expensive at this time. The life cycle costs include development, construction, operation, maintenance, decommissioning, and waste management related costs both for the power plant and for the associated fuel cycle facilities and transportation systems. Another study published by Idaho National Laboratory in 2017 provided the comprehensive set of cost data, along with processes and structures supporting the United States Department of Energy's ongoing evaluation of the advanced nuclear fuel cycles [INL, 2017]. Other studies, such as [INL, 2012], have examined the detailed cost estimates for constructing and operating various types of advanced reactors.

A technical study commissioned by the Ontario Government [CNL, 2016] specifically examined the recycling of Ontario's CANDU reactor used fuel under various scenarios, including reusing fuel in the current CANDU reactor fleet and various FR scenarios. The study showed that all the recycling options had a higher life cycle cost than the current reference plan of emplacing the used CANDU fuel in a deep geological repository, significant initial investment costs, and significant social and technical challenges. In addition, they resulted in the production of significant amounts of long-lived, heat-generating radioactive wastes that required emplacement in a deep geological repository. While the advanced fuel cycle options do offer the potential to produce significant low-carbon baseload electricity over the long term, it also commits the province to this technology for a century or more.

All the proposed advanced fuel cycle schemes are based on the assumption of ongoing or expanding nuclear power programs for many decades or even centuries [OECD/NEA, 2012a, 2013b; EASAC, 2014]. The transition from thermal reactors to FRs has been the subject of several technical and policy studies. Assuming that a country has access to large scale reprocessing facilities for thermal reactor fuel, the cost of obtaining enough plutonium for an initial core loading is in the $1-billion range [MIT, 2011]. (Once started up with plutonium or other enriched fissile material, the reactor can be refueled with depleted uranium or processed used nuclear fuel from thermal reactors, depending on its design.)

In addition to being a significant cost, the rate at which the plutonium can be supplied limits the speed at which the FRs can be deployed. Most scenarios studied (e.g., in France and Japan) require 50 to 100 years or more to transition from thermal reactors to FRs in a stepwise fashion, and a further several hundred years or more to effectively consume the used fuel from current LWRs, assuming a large fleet of FRs. (See, for example, [MIT, 2011], [OECD/NEA, 2012a, 2013b], and [EASAC, 2014].) This long transition time imposes a commitment on future generations to operate and maintain a nuclear power program (including periodic replacement of the nuclear fleet and associated fuel cycle facilities), but it also gives them access to significant quantities of low-carbon energy, should they choose to exploit this source of energy.

Many of the studies point out that as an alternative to the used nuclear fuel from current reactors, there is sufficient depleted uranium available (from LWR fuel enrichment) to sustain such a system globally for many centuries, if not millennia. In fact, the use of existing depleted uranium is often the preferred fuel, since it is widely available and relatively clean both radiologically (low dose rate) and isotopically (free of fission products and other contaminants). More than 1 million tonnes of depleted uranium are currently stockpiled around the world.

To put the FR fuel usage in perspective, if each FR consumed 500 kilograms of fuel per year, the current ~57,000-tonne inventory of used fuel in Canada [NWMO, 2018] could be consumed as fuel over about 100,000 reactor years of operation (e.g., a fleet of 100 reactors operating for 1,000 years). Based on a design life of about 60 years, 16 generations of reactors would be required over 1,000 years, for a total of 1,600 reactors built, operated and decommissioned.

In theory, the required time span to consume most of the problematic transuranic elements (i.e., plutonium and minor actinides) in the used fuel could be reduced to within a hundred years if they were to be completely separated from the U-238 in the used fuel, and there was no delay in FR startups. These would then be consumed first in the FRs while storing the depleted U-238 for future fuel. In practice, however, it has not been possible to achieve the high degree of separation on an industrial scale due to limitations of the separation processes, resulting in a U-238 waste stream that still requires careful long-term management.

The fuel cycles will each produce a range of radioactive wastes of differing characteristics in different relative amounts. This is shown graphically in Figure 2. Note that the figure is indicative only and is not meant to show precise amounts relative to different waste types or fuel cycles. These relationships will depend on the exact design and operation of the facilities. In all cases, each of the fuel cycles will produce at least one waste stream that requires emplacement in a deep geological repository due to its long-lived radionuclide content and/or decay heat generation.

Another area of research is in used fuel reprocessing and partitioning. Current reprocessing technology is based on wet chemistry. The UO_2 used fuel is dissolved in concentrated acids, then subject to a series of chemical steps to separate out the various constituents. Descriptions of the various process used can be found in the technical literature, such as [IAEA, 2010] and [OECD/NEA, 2012b]. Since the used nuclear fuel and resulting products are highly radioactive, all this needs to be done using remotely operated, heavily shielded systems. Even routine maintenance needs to be done remotely due to residual contamination in the equipment. The reprocessing and partitioning steps also result in large volumes of chemically complex wastes. Some of this material can be recycled back into the process, but most eventually end up as radioactive waste that must be stabilized for storage, then ultimately placed in a repository [MIT, 2011; MIIS, 2013].

Most FR scenarios rely on different fuel types than those that are currently used, such as metallic fuels, molten salts or silicon carbide/graphite coated fuel particles. These fuel types would be reprocessed using a different technology than the current wet chemical processing technology. A non-aqueous technology ("pyro-processing") is being developed for some of these fuels. However, although this has been employed in prototype FRs in the past (e.g., the United States Experimental Breeder Reactor program of the 1950s to 1980s [IAEA, 2012]) and has been proposed for other systems, such as Integral Fast Reactors and PRISM [Triplett et al., 2012], pyro-processing has not yet achieved commercial scale implementation. (See, for example, Iizuka et al. in [OECD/NEA, 2012a].) Recycling fuel with these alternative technologies will still be complicated as they will be operating at high temperatures with very radioactive materials. The complexity will also depend on whether there is a need to provide high separation of some undesirable actinides and fission products in the fuel.

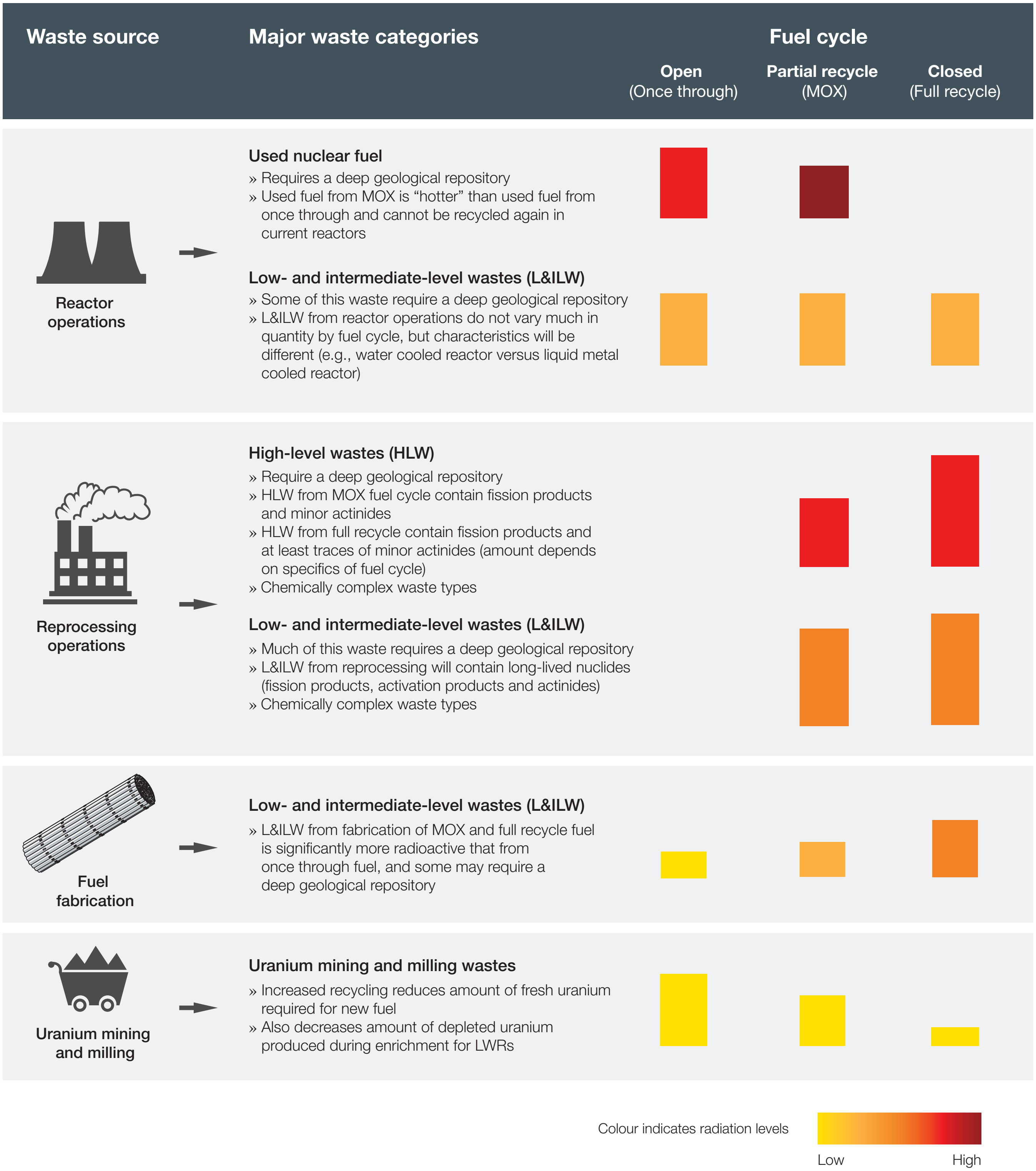

Figure 2: Illustration of wastes produced by different fuel cycles.

Several countries that operate both CANDU type reactors with natural uranium fuel and LWRs with enriched uranium fuel (China, South Korea and India) are also researching or developing synergistic fuel cycles for managing their used LWR fuels, such as DUPIC ("Direct Use of Pressurized water reactor fuel In CANDU") and NUE. After mechanical, thermal and/or chemical processing to resize the fuel pellets and remove volatile fission products, their used LWR fuel is reconfigured as CANDU fuel bundles and introduced into their CANDU reactors to extract additional energy. Note that these technologies are designed for managing LWR fuels and are not applicable in Canada, since Canadian utilities do not currently operate LWRs and the technologies cannot be used to recycle used CANDU fuel in other CANDU reactors.

The transmutation of actinides can also be carried out in an ADS, where high-energy neutrons produced by an accelerator are directed at a blanket assembly containing the waste (actinide elements) along with fissionable fuel. Unlike a conventional nuclear reactor or a FR, this is a sub-critical system: the nuclear reaction stops when the accelerator is turned off. Significant electrical power is required to generate the neutrons. Research is underway in Europe, Japan and elsewhere to use ADSs for transmuting long-lived radionuclides in dedicated systems. The ADS approach can potentially accept a wide isotopic mix in the blanket assembly, providing very efficient transmutation actinides and some other long-lived radionuclides. However, the technology has not yet advanced much beyond the theoretical stage, and the availability of continuous high-power neutron beams is currently a key limiting factor. Research results are reported at scientific conferences and meetings such as the 4th International Workshop on ADSR systems and Thorium [CERN, 2016], OECD NEA's 3rd International Workshop on Technology and Components of Accelerator-Driven Systems [OECD/NEA, 2016a], and OECD NEA's 15th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation [OECD/NEA, 2018a].

Other proposals include the introduction of SMRs. SMRs can vary significantly in size and design concepts. SMRs up to a few tens of megawatts in size are being proposed for use in remote (i.e., off-grid) communities and resource extraction sites that currently rely on small scale fossil fuel generating plants to provide heat and/or electricity [HATCH, 2016]. SMRs up to a few hundreds of megawatts in size could be used on small grids. The reactors are based on a variety of non-CANDU technologies, including liquid metal cooled, molten salt cooled and light water cooled designs. Detailed descriptions can be found elsewhere, such as in [IAEA, 2018b, 2018c] and [EPRI, 2015].

There are currently no active environmental assessments or licence applications underway for any of these proposals. However, the Canadian Nuclear Safety Commission (CNSC) completed Phase 1 and has started Phase 2 of the pre-licensing review of a Canadian-designed molten salt cooled reactor proposed by Terrestrial Energy Inc. [CNSC, 2017, 2018]. Four other SMR designs currently undergoing a CNSC Phase 1 assessment are a gas cooled reactor proposed by Ultra Safe Nuclear Corporation/Global First Power, a sodium cooled reactor proposed by Advanced Reactor Concepts Ltd., a molten salt reactor proposed by Moltex Energy, and a light water cooled reactor proposed by SMR, LLC. (a Holtec International Company). The CNSC's Phase 1 assessment of a lead cooled reactor proposed by LeadCold Nuclear Inc. is on hold at vendor's request. Several other vendors have indicated that they will be submitting pre-licensing review applications in the near future [CNSC, 2018].

In addition, Canadian Nuclear Laboratories (CNL) is also seeking to establish partnerships with vendors of SMR technology to develop, promote and demonstrate the technology in Canada [CNL, 2017]. CNL has launched an invitation to site Canada's first SMR, has initiated the process for construction and operation of SMR demonstration project at Atomic Energy of Canada Limited sites [CNL, 2018a], and received responses from four SMR project proponents [CNL, 2018b].

Natural Resources Canada also initiated the SMR Roadmap project with interested provinces, territories and power utilities to identify the opportunities for on- and off-grid applications of SMRs in Canada. The Roadmap report was published in November 2018, containing more than 50 recommendations in areas such as waste management, regulatory readiness and international engagement [SMR, 2018].

The NWMO will continue to monitor the situation and will evaluate the implications and options for any new reactors as part of the review of the APM approach.

Observations and conclusions

A number of comprehensive technical and strategic reviews of advanced fuel cycles, including RP&T programs and issues have been carried out in recent years by various national and international organizations. These studies and work programs are monitored as part of the NWMO's ongoing watching brief on advanced fuel cycle technologies. Consistent with previous reports, the main observations from the review of current international research are:

- Regardless of the fuel cycle, there will be long-lived radioactive wastes. There is general agreement internationally that deep geological repositories offer the best solution for safe, long-term management of residual long-lived wastes from any fuel cycle.
- Although RP&T has the potential to reduce the volume of used nuclear fuel and high-level waste for placement in a deep geological repository, it also significantly increases the quantity of long-lived intermediate-level waste (which also requires a deep repository for long-term management) and does not significantly reduce the underground footprint of the repository. (For used fuel and high-level waste, repository size is based primarily on heat generation rate, not on volume of the waste. This is a function of the amount of energy extracted from the fuel, so it remains relatively constant per unit energy produced, regardless of fuel cycle.)
- Advanced fuel cycles with both RP&T and advanced (fast) reactors are at least several decades away from being ready for wide scale commercialization due to the time required for the technical research, and to develop and demonstrate the advanced reactor technologies. High cost and broad public acceptance issues that may accompany used fuel reprocessing and/or the "first-of-a-kind" reactor designs may also inhibit their demonstration and deployment in the near term. Once a decision has been taken to deploy such fuel cycles, it may take some decades further to fully transition from current fuel cycles to the new ones, and decades to centuries to realize any waste management benefit from their implementation.
- There continues to be an interest shown in Canada and internationally in developing SMRs. The proposed SMRs use non-CANDU fuel cycles, some employing liquid fuels, which will likely add new types of used fuel waste to manage. One concept considers the option of recycling used CANDU fuel. Several designs are currently undergoing preliminary design or design certification reviews by regulators in a few countries, including Canada.
- Based on the current cost of uranium, the life cycle cost of advanced fuel cycles is higher than once-through fuel cycle, due to the costs of developing and constructing the new generation reactors, reprocessing facilities and fuel fabrication plants.

- The United Kingdom, one of the countries currently engaged in fuel reprocessing, are discontinuing this practice due to the high costs of replacing aging reprocessing facilities compared to the lower cost option of direct placement of used fuel in a deep geological repository.
- Some countries, notably China, Russia, and India, continue to develop or construct prototype advanced reactors and the associated fuel cycle facilities. China and India are also planning to construct deep geological repositories to manage the high-level wastes from their programs. Russia is planning to develop a closed fuel cycle which would include mandatory reprocessing of used nuclear fuel, for reuse in the existing reactors or in advanced reactors.
- A few other countries, notably Taiwan and Korea, are contemplating reprocessing existing used fuel as a means to extend the used fuel storage capacity at their reactor sites. Their wet storage bays are near capacity, and they do not have the option to expand used fuel storage due to political or technical constraints. Therefore, their only option in the short term to allow the reactor fleet to remain in operation is having the used fuel reprocessed and storing the resulting high-level waste in order to free up space in the wet storage bays for additional used fuel. However, new facilities would still be required for storage of the resulting high-level waste and intermediate-level waste from reprocessing.

The main conclusions from the NWMO perspective are:

- Advanced fuel cycles are not likely to be implemented in Canada on a commercial scale in the near future.
- The introduction of SMRs in Canada would result in new used fuel waste types that will need to be managed. The impact of these potential new wastes on the NWMO program will need to be evaluated as part of the consideration of the SMR technologies.
- Waste arising from advanced fuel cycles would be managed by the NWMO in a manner that is safe, socially acceptable, technically sound, environmentally responsible, and economically feasible.
- The NWMO will continue maintaining a watching brief on advanced fuel cycle developments that could have an impact on Canada's future waste management requirements.

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