

# 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 priority;
- » 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 in the near future.
- » Waste arising from alternative fuel cycles would still need long-term management such as through a deep geological repository.
- » The NWMO should maintain its watching brief on alternative fuel cycle developments.

Note that the responsibility for developing and introducing new nuclear fuel cycles in Canada rests with the nuclear power producers, as well as the federal and provincial governments, which set the nuclear and energy mix policies and plans. Should a new fuel cycle emerge in the future, the NWMO would be responsible for the long-term management of the resulting nuclear fuel waste.

## Executive Summary

The NWMO maintains a watching brief on worldwide developments in advanced fuel cycles, such as Reprocessing, Partitioning & Transmutation (RP&T) technology and their application. Previous detailed technical reports [Jackson, 2008, 2009, 2010] and summary watching brief reports [NWMO, 2011, 2012a, 2013, 2015, 2016] are available on the NWMO website. This report focuses on the current status and a summary of recent international activities since the 2016 Watching Brief was published.

Recycling of used fuel in current generation reactors is generally done for strategic national energy security reasons, rather than for economic or waste management reasons. Indeed at current uranium prices, recycling used fuel is considerably more costly than the open cycle and does not eliminate the need for long-term management of residual high-level wastes, as well as the additional low- and intermediate-level wastes produced during the recycling process. There are no countries that currently follow a fully closed fuel cycle on an industrial scale.

Research and development work continued in 2017 in various countries and international collaborative programs to review and assess the technology and implications of advanced fuel cycles, including fully closed cycles based on reprocessing, partitioning and transmutation (RP&T). Findings were presented at a number of international conferences and technical meetings.

Similar to previous NWMO watching briefs on RP&T and advanced fuel cycles, the basic observations of 2017 annual review are:

- » Some form of deep geological repository is required regardless of the fuel cycle in order to be able to deal with long-lived radioactive wastes.
- » The waste management benefits of advanced fuel cycles are uncertain. 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 (when combined with advanced fuel cycles using FRs), 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 high-level waste and used fuel, 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 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 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 to fully transition from current fuel cycles to the new ones, and decades to centuries to realize any waste management benefit from their implementation [OECD/NEA, 2013b].
- » Recently, there has been some interest shown in Canada and internationally in developing small modular reactors (SMRs). All of the currently proposed SMRs use non-CANDU fuel cycles, some employing rather exotic designs based on liquid fuels. This will not affect existing CANDU used fuel waste, but will add new and different types of nuclear fuel waste to manage. Several designs are currently undergoing preliminary design reviews by regulators in a few countries, including Canada.
- » Based on the current cost of uranium, the lifecycle 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. If such fuel cycles could be developed, the cost and project risks for implementing them on a commercial scale would currently make them very unattractive and financially risky for utilities to deploy.

- » Some countries currently engaged in fuel reprocessing, such as the United Kingdom, have decided to discontinue 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.
- » A few countries with rapidly expanding energy needs and nuclear power programs, such as China and India, are developing or constructing prototype advanced reactors and the associated fuel cycle facilities. These countries are also planning to construct deep geological repositories to manage the high-level wastes from their programs.
- » A few other countries, such as 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, either wet or dry, 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 are required for storage of the resulting HLW from reprocessing. (Most other countries do not have this issue because they have the much less expensive option of dry storage of older used fuel and have sufficient capacity to expand the storage as needed.)

## 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 (e.g. LWR) is used as fuel in another reactor type with a lower uranium enrichment requirement (e.g. CANDU); 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.

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 into possible future FRs. Recycled uranium from light water reactors (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	Decided to Cease Having Used Fuel Reprocessed	Planning Direct Placement of Used Fuel in a Repository
	Existing	Planned			
Belgium				✓	✓
Canada					✓
China <sup>(3)</sup>		✓			✓ <sup>(4)</sup>
Czech Republic				✓ <sup>(7)</sup>	✓
Finland				✓ <sup>(7)</sup>	✓
France <sup>(3)</sup>	✓ <sup>(2)</sup>				
Germany				✓	✓
Hungary				✓ <sup>(7)</sup>	✓
India <sup>(3)</sup>	✓				
Japan		✓ <sup>(6)</sup>	✓		
Korea, Rep. of					✓
Mexico					✓
Netherlands			✓ <sup>(5)</sup>		
Pakistan <sup>(3)</sup>					
Romania					✓
Russia <sup>(3)</sup>	✓				
Slovakia				✓ <sup>(7)</sup>	✓
Slovenia					✓
Spain					✓
Sweden				✓	✓
Switzerland				✓	✓
Ukraine				✓ <sup>(7)</sup>	✓
United Kingdom <sup>(3)</sup>	✓ <sup>(1)</sup>			✓	✓
United States <sup>(3)</sup>				✓	✓

(1) The United Kingdom plans to cease reprocessing at end of current contracts, expected about 2020.

(2) France supplies commercial reprocessing services to a number of European and Asian countries.

(3) China, France, the United Kingdom, Russia, 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 MTHM. 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 2018), 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/yr)	Status
China	Gansu	200	Under construction (expected ~2020)
France	UP1, Marcoule	600	Shut down/Decommissioning
	UP2-400, La Hague	400	Shut down/Decommissioning
	UP2-800, La Hague	800	In operation
	UP3, La Hague	800	In operation
India	(4 facilities)	~330 (total)	In operation
Japan	Tokai	90	Shut down/Decommissioning
	Rokkasho	800	In commissioning, expected ~2018?
Russian Federation	RT-1, Mayak	400	In operation
	MCC, Zheleznogorsk	60	In operation
	RT-2, Zheleznogorsk	700 + 800	Under construction (expected ~2025?)
United Kingdom	MAGNOX, Sellafield	1500	In operation, expected shut down 2020
	THORP, Sellafield	900	In operation, expected 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 that must be solved before they can be implemented on an industrial scale. Indeed, a report co-authored by the European Commission's Joint Research Centre and the European Academies' Science Advisory Council states that *"Furthermore, the development of fast neutron reactor technology has been more difficult than expected"* [EASAC, 2014].

It is not clear whether there are many waste management benefits from implementing advanced fuel cycles. While some of the advanced fuel cycles can address potential waste management issues (such as increasing the waste storage density in some repository designs or using previously separated plutonium), many of them make waste management issues more complex because they result in a number of chemically complicated radioactive waste streams that must be suitably processed and conditioned before being placed in a deep geological repository anyway. Other concepts rely on long-term (several hundred years) surface storage to allow radioactivity and its associated heat load to decay before placing the wastes into a repository.

Beyond the primary benefit of energy security with these systems, a secondary benefit of the advanced fuel cycles is that it may reduce the demand for space in a high-level waste repository. However, this benefit can only be realized if alternative methods of managing the large volumes of long-lived and/or heat-generating secondary waste resulting from reprocessing can be found and if some of the separated fission product wastes are stored for several hundred years 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 recent comprehensive review of used fuel management options for Korea conducted by the James Martin Center for Nonproliferation Studies of the Monterey Institute of International Studies states: *"...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"* [MIIIS, 2013].

In the US, after the decision to stop the Yucca Mountain repository licence application, the Blue Ribbon Commission on America's Nuclear Future (BRC) conducted an extensive review in 2010 and 2011 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, 2012a], the BRC stated (among other things):

*» The conclusion 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.*

Additional detailed reports were also issued by each of the three BRC subcommittees (Reactor & Fuel Cycle Technology, Transportation & Storage, and Disposal) [U.S. BRC, 2012b, c, d]. The U.S. government is still considering how it will respond to the BRC recommendations.

A similar conclusion was also reached by the recent Australian Royal Commission into the Nuclear Fuel Cycle [Government of South Australia, 2016]:

*» There is international consensus that deep geological disposal is the best available approach to long-term disposal of used fuel.*

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

- » 8th International Symposium on Super-Critical Water-Cooled Reactors, ISSCWR-8 (March 2017, Chengdu, China) [ISSCWR, 2017];
- » Annual World Nuclear Fuel Cycle conference (April 2017, Toronto) [WNA, 2017];
- » American Nuclear Society's International Congress on Advances in Nuclear Power Plants, ICAPP2017 (April 2017, Kyoto, Japan) [ICAPP, 2017];
- » 18th International Conference on Emerging Nuclear Energy Systems, ICENES 2017 (April 2017, Hefei, China) [ICENES, 2017];
- » International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development, FR17 (June 2017, Yekaterinburg, Russian Federation) [IAEA, 2017a];
- » Generation 4 Nuclear reactor systems for the future, ESNII 2017 (June 2017, Saclay, France) [ESNII, 2017];
- » 25th International Conference on Nuclear Engineering, ICONES 2017 (July, 2017, Shanghai, China) [ICONES, 2017];
- » American Nuclear Society's 13th International Topical Meeting on Nuclear Applications of Accelerators, AccApp 17 (July 2017, Quebec City) [ANS, 2017];
- » GLOBAL 2017 International Nuclear Fuel Cycle Conference (September 2017, Seoul, Korea) [GLOBAL, 2017];
- » Materials Research Society, Scientific Basis for Nuclear Waste Management 2017 (October 2017, Sydney, Australia) [SBNWM, 2017];

Papers presented at these conferences, as well as technical reports published by the OECD Nuclear Energy Agency (NEA) [e.g., OECD/NEA, 2009-2016], International Atomic Energy Agency (IAEA) [e.g., IAEA, 2012-2017], French Commissariat à l'énergie atomique et aux énergies alternatives (CEA) [e.g., CEA,

2015], U.S. Nuclear Regulatory Commission [U.S. NRC, 2012], Electric Power Research Institute (EPRI) [e.g., EPRI, 2012-2017], the UK Radioactive Waste Management agency [RWM, 2017], and various international collaborative projects (such as the European Sustainable Nuclear Energy Technology Platform [SNETP, 2012-2015], and Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution [ASGARD, 2013] projects) were reviewed and monitored by the NWMO as part of 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 prototype fast reactors currently in operation or under construction in a few countries such as China, India and Russia, all of the commercial nuclear power reactors in operation or under construction around the world today are based on thermal neutrons. In this type of reactor, a moderator is used to slow down (or thermalize) the high energy neutrons produced by the fission reaction so that they can induce further fission in the U-235 and/or Pu-239 isotopes in the nuclear fuel. Moderating materials include normal or light water (used in most non-CANDU reactors around the world), heavy water (used in CANDU reactors) and graphite (mainly used in gas cooled reactors). The moderating materials have different properties for interacting with the neutrons. For example, heavy water moderated reactors can sustain a nuclear chain reaction in natural (un-enriched) uranium, which contains about 0.7% of U-235 with the rest being U-238. On the other hand, light water (used in many other places in the world in boiling water reactors (BWRs) and pressurized water reactors (PWRs), collectively known as LWRs) requires a higher concentration of U-235 (typically 3% to 5%) to work. 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% 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 burdens 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 reason is based on the premise that if used fuel from existing reactors can be recycled into advanced reactors (e.g. fast reactors), that there will be an ongoing nuclear power program for many decades (or even centuries) and 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.

Note also 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; NWMO, 2012b; Sandia, 2012; EASAC, 2014].

In any event, fully implementing RP&T requires the commercial scale deployment of advanced systems, such as FRs as shown in Figure 1, or accelerator-driven systems, 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, 2013c] 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 [GIF, 2014], [IAEA, 2016].

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 very 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 practiced for commercial nuclear power reactors (i.e., greater than 20% U-235 versus 3% to 5% 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) [Transatomic Power, 2014]. 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% enrichment. Many molten salt designs also use on 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 melt-downs (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].

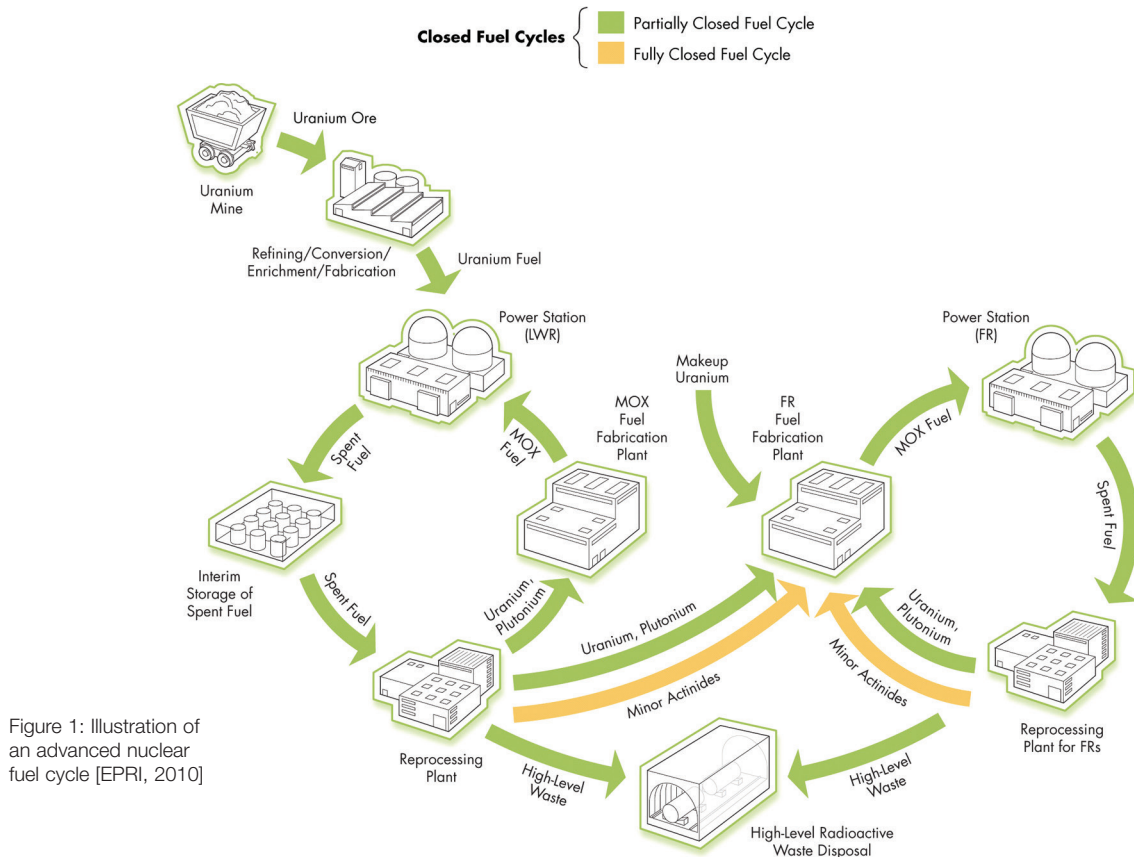
Cost is also an important consideration. In order to be successfully deployed on a commercial basis, the lifecycle cost of producing electricity with advanced reactors and fuel cycles must be lower than for other production methods, including current nuclear power plants and non-nuclear technologies. A major study published in 2013 by the OECD/NEA [OECD/NEA, 2013a] looked at lifecycle costs for various fuel cycle options and concluded that the once through fuel cycle was the least expensive at this time. The lifecycle 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. Other studies, such as [INL, 2012], have examined the detailed cost estimates for constructing and operating various types of advanced reactors.

A recent technical study commissioned by the Ontario Government [CNL, 2016] specifically examined the recycling of Ontario's CANDU reactor used fuel under various scenarios including re-using fuel in the current CANDU reactor fleet and various fast reactor scenarios. The study showed that all of the recycling options had a higher lifecycle 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, as discussed in other studies on implementing the advanced fuel cycles [OECD/NEA, 2012b, 2013b; EASAC, 2014]. The transition from thermal reactors to FRs is the subject of several recent 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 step-wise 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, 2009, 2012b, 2013b], Warin and Boullis in [OECD/NEA, 2012a], and [EASAC, 2014].) This long transition time imposes a commitment on future generations to operate and maintain an advanced 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 in addition to the used nuclear fuel, there is sufficient depleted uranium available (from LWR fuel enrichment) to sustain such a system globally for many centuries, if not millennia, since each reactor would typically consume only a few hundred kilograms of uranium or other heavy actinides per year as makeup fuel. 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 (as of June 2017) ~55,000-tonne inventory of used fuel in Canada [NWMO, 2017] could provide electricity for some 100,000 reactor years of operation (e.g., a fleet of 100 reactors operating for 1,000 years). Since the reactors are currently designed for a life of about 60 years, 16 generations of reactors would be required to give the required lifespan of 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 start-ups. 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.

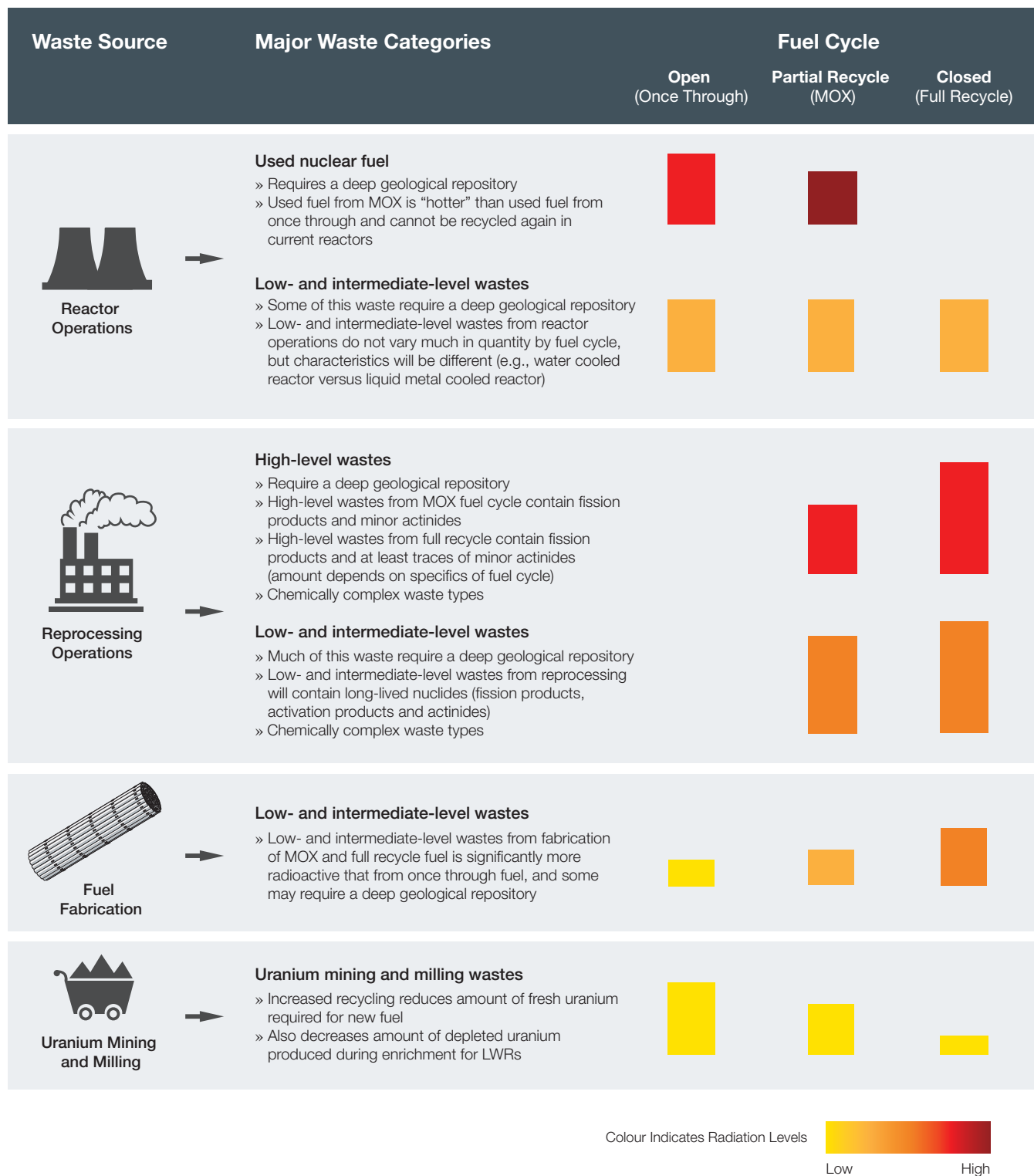


Figure 2: Illustration of wastes produced by different fuel cycles

Another area of research is in used fuel reprocessing and partitioning. Current reprocessing technology is based on wet chemistry. The 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 [OECD/NEA, 2012c]. 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; MII, 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 are not compatible with the current wet chemical processing technology used for LWR uranium-oxide-based fuels. A non-aqueous technology (pyro-processing) is being developed for these fuels. However, although this has been employed in prototype FRs in the past (e.g., the U.S. Experimental Breeder Reactor (EBR) program of the 1950s to 1980s [IAEA, 2012]) and has been proposed for other systems, such as IFR 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].) In addition, many FRs require complex reprocessing facilities to remove the buildup of undesirable actinides and fission products in the fuel resulting from multiple recycling. Remote handling is also required for recycled fuel fabrication due to the presence of nuclides which emit high-energy gammas.

Several countries that operate both CANDU type reactors with natural uranium fuel and LWRs with enriched uranium fuel (such as 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 (Natural Uranium Equivalent). 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 accelerator-driven system (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 fast reactor, 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 utilize ADS 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 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] and the OECD-NEA's 3rd International Workshop on Technology and Components of Accelerator-Driven Systems [OECD/NEA, 2016a].

Other proposals include the introduction of small modular reactors (SMRs). SMRs are up to a few tens of megawatts in size and are being proposed for use in remote (i.e., off-grid) communities and resource extraction sites which currently rely on small-scale fossil fuel generating plants to provide heat and/or electricity [HATCH, 2016]. 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 [EPRI, 2015] and [IAEA, 2016].

There are currently no active environmental assessments or licence applications underway for any of these proposals. However, the CNSC has completed a Phase 1 pre-licensing review of a Canadian designed molten salt cooled SMR [Terrestrial Energy, 2016], [CNSC, 2017]. Two other SMR types currently undergoing a CNSC Phase 1 assessment are a lead-cooled reactor and a gas-cooled reactor. Several other vendors have indicated that they will be submitting pre-licensing review applications in the near future, including sodium-cooled, gas-cooled and molten salt designs [CNSC, 2017]. 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]. 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 Adaptive Phased Management approach.

Although current research programs show the wide variety of work that is being carried out on very specific topics in a number of countries, they also demonstrate that transmutation technology is still far away from wide-scale practical implementation since none of the work has progressed beyond the laboratory environment. There are many basic technical challenges facing these advanced technologies, such as development of suitable materials to withstand the very high temperatures, pressures and/or corrosive nature of the process fluids while operating in the high-energy and high-flux neutron fields required in the core for these reactors, as well as the development of suitable fuel matrices [OECD/NEA, 2011]. Some of these challenges related to materials and fuels would be “showstopper” issues for the advanced reactors if they cannot be resolved. However, the potential benefits of advanced fuel cycles have resulted in the establishment of various international consortia (e.g., the Generation IV International Forum [GIF, 2014]) and commercial entities pursuing various designs and fuel cycle options.

Note also that used nuclear fuel contains a number of commercially valuable conventional elements such as platinum group metals and rare earths. Potentially, these could be extracted using advanced reprocessing and chemical techniques if a cost-effective method can be developed to remove any residual radioactivity and if the broader public is willing to accept its origin.

## Observations and Conclusions

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

- » Regardless of the fuel cycle, some form of deep geological repository is required in order to be able to deal with 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.
- » It is not clear whether there are any significant benefits to waste management of existing CANDU wastes from advanced fuel cycles. The use of advanced fuel cycles may not significantly reduce the underground footprint of the repository when the large volumes of long-lived and/or heat-generating secondary wastes are taken into account.
- » Although prototype FRs have been in existence since the 1950s, advanced fuel cycles are still many decades away from being ready for widespread commercialization due to the time required for additional technical research to improve the materials and reliability of the reactors and supporting fuel cycle facilities. In addition, many more decades are required to fully transition from current reactors to advanced fuel cycles.
- » The use of depleted uranium is generally considered to be the better option as a FR makeup fuel over the use of recycled thermal reactor fuel, since it is widely available and has very low specific radioactivity, whereas reprocessed uranium or used fuel will be very radioactive.
- » Broad public acceptance issues related to siting and construction of large-scale "first-of-a-kind" nuclear facilities are also likely to delay the demonstration and deployment of advanced fuel cycles in the near term in many countries.
- » The lifecycle cost of advanced fuel cycles is higher than once through fuel cycles, due to the high costs of developing and constructing the new generation reactors, reprocessing facilities and fuel fabrication plants. However, some countries with rapidly expanding energy needs have chosen to pursue advanced fuel cycles for national energy policy reasons, while other countries are considering them to deal with specific issues, such as previously separated plutonium.
- » The introduction of small modular reactors into Canada will result in new nuclear fuel waste types that will need to be managed. The impact of these potential new wastes on the APM program will need to be evaluated in the future.

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.
- » Waste arising from alternative 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 maintain a watching brief on alternative fuel cycle developments that could have an impact on Canada's future waste management requirements.

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