NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

(2019 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 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. 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 long-lived 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 publishing this watching brief since 2008. This edition of the watching brief paper outlines recent international research and developments in nuclear fuel cycles, and discusses their potential applicability to Canada. The main conclusions are:

- There continues to be international interest and research in new fuel cycles, but no technical breakthroughs that change the previous conclusion regarding the APM approach for management of present Canadian used nuclear fuel.
- The introduction of small modular reactors (SMRs) in Canada would result in small quantities of 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 [e.g., NWMO, 2018a] are available on the NWMO website.

Research and development work continued in 2019 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.

Current fuel cycles

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 more in a current reactor type; and
- “Closed” or “full recycle,” in which the used fuel is reprocessed to recover fissile isotopes like plutonium and other actinides, and 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.

A particular “partial recycle” scenario is recycling the uranium from light water reactor (LWR) used fuel into reactors, after which the fuel is considered to be waste. Currently, China, which has both LWRs and CANDUs, is planning to use this approach for some of its fuel.

Other variations can include different combinations of reactors, including combinations of conventional thermal reactors, FRs 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, notably France, the United Kingdom, Russia, and India, reprocess some of their fuel, with some of the resulting MOX fuel used in a “partial recycle” fuel cycle or stored awaiting future recycling in unspecified future reactors. Some countries have reprocessed some fuel in the past, but are no longer doing so now (Belgium, Germany and Switzerland); their reprocessed fuel is being treated as waste.

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.

A summary of global reprocessing capacity for commercial fuels is shown in Table 2. This summary does not include facilities solely for military purposes.

A "closed" fuel cycle requires a FR in order to effectively use the fuel. Almost all commercial power reactors presently in operation are thermal neutron reactors; FR technology is more complicated. Table 3 lists the currently operating or planned FRs for generating electricity.

Advanced fuel cycles are of interest because they use the uranium fuel very efficiently. In particular, some advanced fuel cycles are theoretically almost self-sustainable once they reach equilibrium. However, there are still many scientific and engineering challenges (such as development of suitable materials, and the scale up from experiments to full-sized reactors), 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 should reduce the amount of actinides in the waste and may reduce 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 to allow the decay heat to dissipate. Otherwise, there is no significant benefit to the size or safety of a deep geological repository for the residual long-lived wastes.

This is reflected in various national reviews, which continue to support the need for a deep geological repository. In particular:

- 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.*"
- A 2013 comprehensive review of used fuel management options for Korea concluded: "*…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].
- 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].

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	1,500 900	In operation (expected shut down 2020) Shut down 2018
United States	West Valley	300	Operated 1966-72, decommissioned

Table 3: Summary of operating or under construction fast power reactors

Country	Facility	Capacity (MWe)	Status
Russian Federation	BN-600 BN-800	560 880	Operating since 1980 – sodium pool type Operating since 2016 – sodium pool type
India	PFBR	500	Under construction – sodium pool type
China	CFR-600	600	Under construction – sodium pool type

Technology status for advanced fuel cycles

Research on advanced fuel cycles continues worldwide, and most recent findings were presented in 2019 at various international conferences and technical meetings, including:

- 9th International Symposium on Supercritical-Water-Cooled Reactors, ISSCWR-9 (March 2019, Vancouver, Canada) [CNS, 2019];
- 9th International SMR & Advanced Reactor Summit 2019 (April 2019, Atlanta, United States) [NEI, 2019];
- Annual World Nuclear Fuel Cycle Conference (April 2019, Miami, United States) [WNA, 2019];
- International Congress on Advances in Nuclear Power Plants, ICAPP 2019 (May 2019, Juan-les-Pins, France) [ICAPP, 2019];
- 27th International Conference on Nuclear Engineering, ICONE27 (May 2019, Tsukuba, Japan) [ICONE, 2019];
- International Atomic Energy Agency's (IAEA) International Conference on the Management of Spent Fuel from Nuclear Power Reactors (June 2019, Vienna, Austria) [IAEA, 2019a];
- Global/TopFuel 2019 (September 2019, Seattle, United States) [ANS, 2019];
- 19th International Conference on Emerging Nuclear Energy Systems, ICENES 2019 (October 2019, Bali, Indonesia) [ICENES, 2019];
- Organisation for Economic Co-operation and Development Nuclear Energy Agency's (OECD/NEA) 4th International Workshop on Technology and Components of Accelerator-Driven Systems, TCADS-4 (October 2019, Belgium) [OECD/NEA, 2019a]; and
- Materials Research Society's Symposium EN17 – Structure-Property Processing Performance Relationships in Materials for Nuclear Technologies (December 2019, Boston, United States) [MRS, 2019].

Papers presented at these conferences, as well as technical reports published by the OECD NEA [e.g., OECD/NEA, 2011-2019], IAEA [e.g., IAEA, 2012-2019], 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], the Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution [ASGARD, 2016], and the GEN IV Integrated Oxide Fuels Recycling Strategies [GENIORS, 2017] projects) were 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 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, 2015a,b].

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 ("low energy") neutrons. These reactors currently use moderator materials to slow down the high energy neutrons from the fission reactions – these moderators are usually normal or light water (most non-CANDU reactors), heavy water (CANDU reactors) or graphite (gas cooled reactors). The fuels used in these reactors contain either natural uranium (0.7 per cent U-235, 99.3 per cent U-238) such as in CANDU reactors, or fuel with a higher concentration of fissile U-235 (typically 3 to 5 per cent). Producing this higher U-235 concentration is known as enrichment. Operation of current reactor types requires a continuous supply of fresh uranium as a source of 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 national 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 may not 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 with significant surface storage for decay of heat generating fission products, is there any significant reduction in high-level waste repository space requirements. Even in this case, the reduction in high-level waste repository space is offset by the 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 significantly improve the overall safety of a repository because the transuranic elements have very low mobility in the repository environment. 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, 2017, 2018b].

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, 2013] 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 (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).

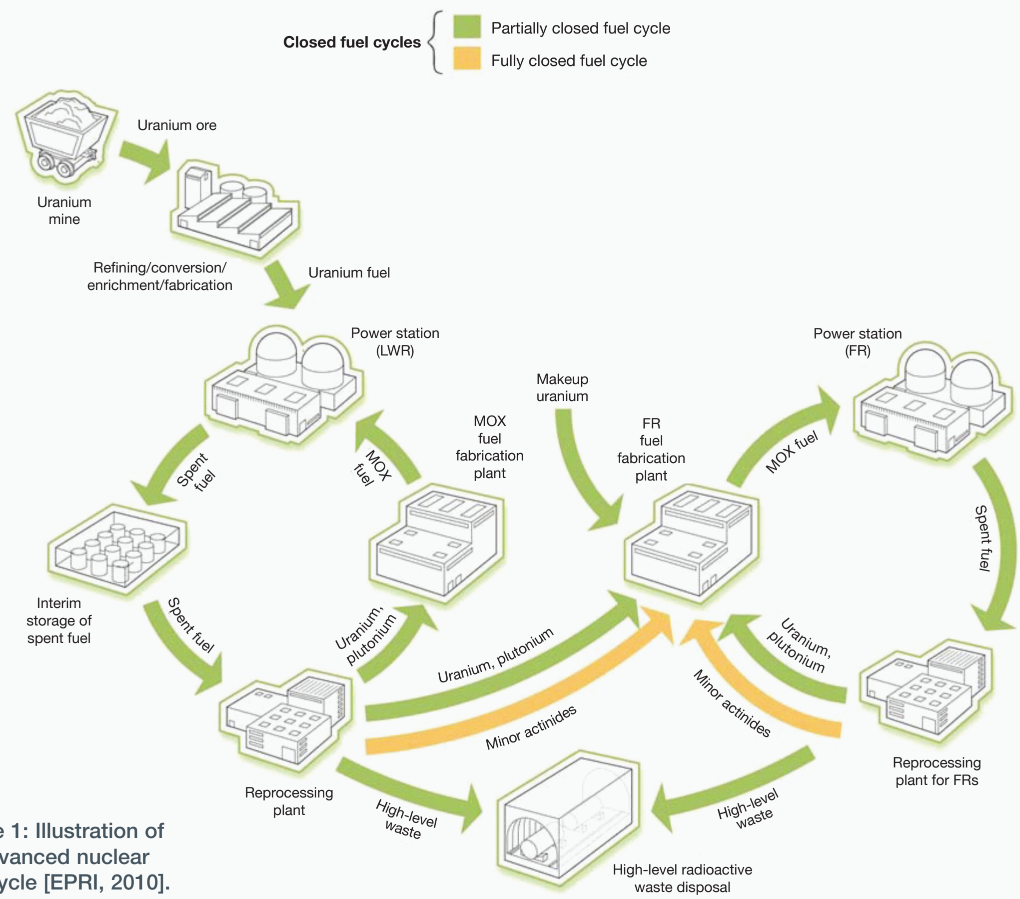

Figure 1: Illustration of an advanced nuclear fuel cycle [EPRI, 2010].

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, 2019b], [GIF, 2018].

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 chemically reactive liquid metal or salt coolants create harsh conditions for any reactor materials. Investigation of materials that can withstand these conditions for 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;
- **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 can supply fuel for an 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 is 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 life cycle cost of producing electricity with advanced reactors and fuel cycles must be lower than for other electricity 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].

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.

In addition to cost, the rate at which the plutonium can be supplied to start and operate the FRs is also an important consideration. 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 gives future generations access to significant quantities of low-carbon energy, but imposes a commitment to operate and maintain a nuclear power program (including periodic replacement of the nuclear fleet and associated fuel cycle facilities).

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 potential FR use of current used CANDU fuel in perspective, if each FR consumed 500 kilograms of fuel per year, the current ~57,000-tonne inventory of used fuel in Canada [NWMO, 2019] could be consumed as FR 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 fast 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 [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 (notably 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.

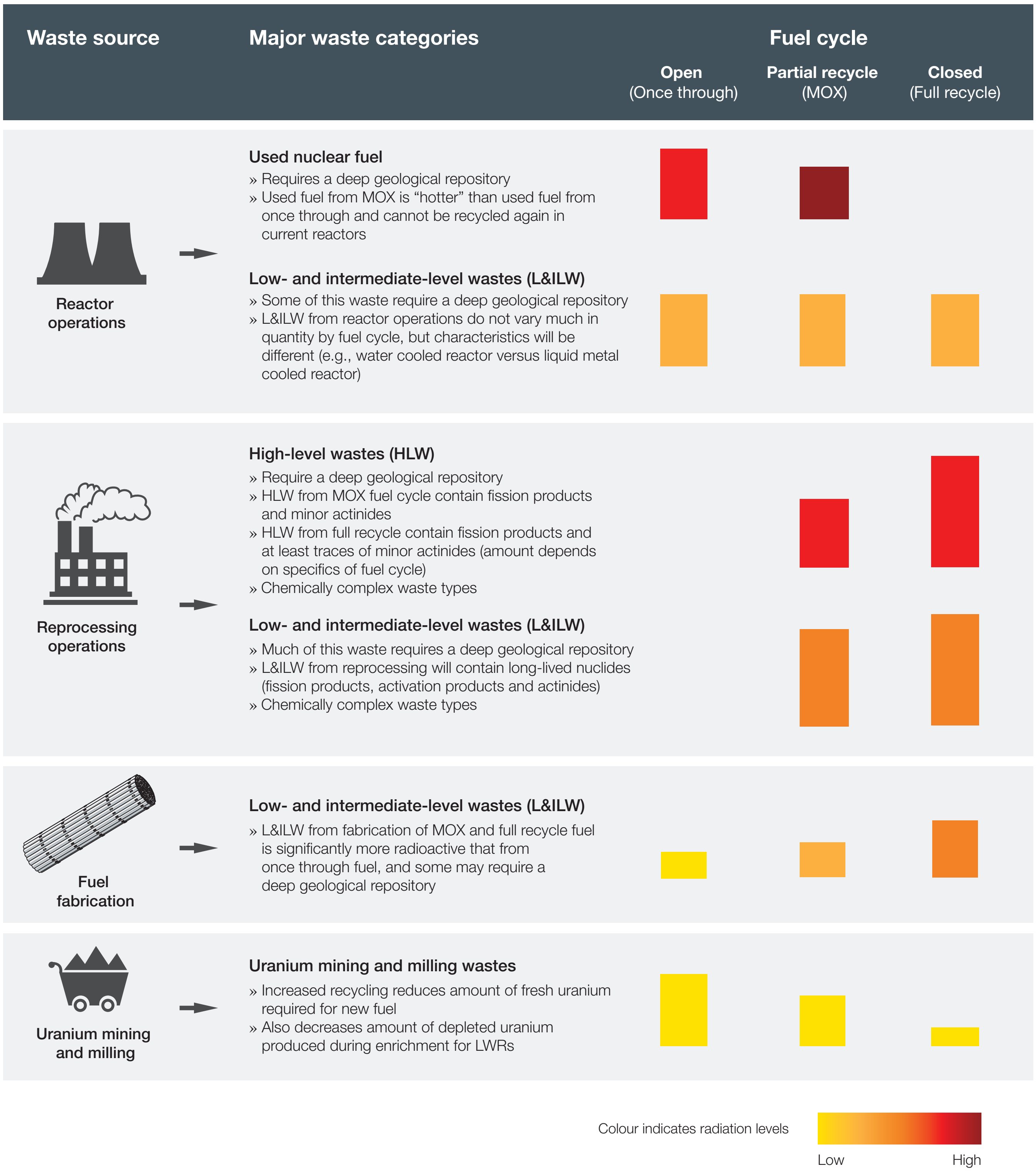

Figure 2: Illustration of wastes produced by different fuel cycles.

A potential fuel cycle option for countries that operate both CANDU type reactors with natural uranium fuel and LWRs with enriched uranium fuel is also researching synergistic fuel cycles for managing their used LWR fuels. This is referred to as DUPIC ("Direct Use of Pressurized water reactor fuel In CANDU") and "natural uranium equivalent" fuel. 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 operate LWRs and the technologies cannot be used to recycle used CANDU fuel in other CANDU reactors. Presently, China, which has both LWRs and CANDUs, is considering this fuel cycle for some of its LWR fuel.

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 OECD NEA's 4th International Workshop on Technology and Components of Accelerator-Driven Systems [OECD/NEA, 2019a].

Small modular reactors

Other proposals include the introduction of SMRs. 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 diesel 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 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, 2019b] and [EPRI, 2015].

Natural Resources Canada 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].

Some utilities have expressed interest in supporting the development of SMR technologies; for example, New Brunswick Power has recently committed to support Moltex Energy and Advanced Reactor Concepts Nuclear for developing and demonstrating an advanced SMR nuclear energy research cluster [NB Power, 2019]. Bruce Power has also committed to the development of SMR technology, including memorandums of understanding with NuScale Power, as well as MIRARCO Mining Innovation and Laurentian University [Bruce Power, 2018a, 2018b]. No licensing activities have been initiated at this time.

In December 2019, a memorandum of understanding was signed between governments of Ontario, Saskatchewan and New Brunswick on collaborating on the development and deployment of SMRs in these provinces.

The Canadian Nuclear Safety Commission (CNSC) completed the Phase 1 and has started the Phase 2 of the pre-licensing review of a Canadian-designed molten salt cooled reactor proposed by Terrestrial Energy Inc. [CNSC, 2017, 2019a]. The CNSC also completed the Phase 1 assessment for a gas cooled reactor proposed by Ultra Safe Nuclear Corporation [CNSC, 2019b], and a sodium cooled reactor proposed by Advanced Reactor Concepts Ltd. [CNSC, 2019c]. Two other SMR designs currently undergoing a CNSC Phase 1 assessment are 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, 2019a].

The Canadian Nuclear Laboratories (CNL) is seeking to establish partnerships with vendors of SMR technology to develop, promote and demonstrate the technology in Canada [CNL, 2017]. At present, four proponents are in various stages of CNL's review [CNL, 2019]. Global First Power has started CNL's Stage 3 for a proposed 5 MWe Micro Modular Reactor (MMR™) (high temperature gas reactor). Three other proponents have completed CNL's pre-qualification stage and have been invited to enter CNL's next stage of detailed review; these are U-Battery Canada Ltd. (4 MWe high temperature gas reactor), StarCore Nuclear (14 MWe high temperature gas reactor), and Terrestrial Energy (190 MWe integral molten salt reactor).

Global First Power has submitted to the CNSC the initial application for a Licence to Prepare Site [GFP, 2019a, 2019b]. Global First Power, Ultra Safe Nuclear Corporation, and Ontario Power Generation propose to construct and operate a 5 MWe MMR™ plant on Atomic Energy of Canada Limited's property at the Chalk River Laboratories. In July 2019, the federal government issued a Notice of Commencement of an environmental assessment for this SMR project at the Chalk River Laboratories [CNSC, 2019d].

The NWMO will continue to monitor the development of SMRs and implications of new reactors on used nuclear fuel as part of its ongoing review of the APM approach.

Observations and conclusions

A number of technical and strategic reviews of advanced fuel cycles have been carried out in recent years by national and international organizations. These studies are monitored as part of the NWMO's watching brief on advanced fuel cycle technologies. Consistent with previous reports, the main observations from the current review of 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 not 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 centuries to realize any waste management benefit from their implementation.

- There continues to be interest 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. An application was submitted in 2019 to the CNSC for a Licence to Prepare Site for a 5 MWe Micro Modular Reactor (MMR™) plant at the Chalk River Laboratories.
- 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 will discontinue its fuel reprocessing 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.

The main conclusions from the NWMO perspective are:

- There continues to be international interest and research in new fuel cycles, but no technical breakthroughs that change the previous conclusion regarding the APM approach for management of present Canadian used nuclear fuel.
- The introduction of SMRs in Canada would result in small quantities of 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.

References

ANS, 2019. Global/TopFuel 2019, organized by the American Nuclear Society, September 22-26, 2019, Seattle, United States.
(globaltopfuel.ans.org)

ASGARD, 2016. Final Report Summary – ASGARD (Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution), Sweden.
(www.asgardproject.eu)

Bruce Power, 2018a. “Bruce Power signs $1 million MOU for sustainable energy research group,” Bruce Power news release, April 6, 2018.
(www.brucepower.com)

Bruce Power, 2018b. “Bruce and NuScale collaborate on Canadian SMR business case,” Bruce Power news release, November 27, 2018.
(www.brucepower.com)

CEA, 2015. Avancées des recherches sur la séparation-transmutation et le multi-recyclage du plutonium dans les réacteurs à flux de neutrons rapides. Report prepared by CEA, June 2015.
(www.cea.fr)

CNL, 2016. A Feasibility Study on the Recycling of Used CANDU Fuel, report # 153-124900-REPT-002. Prepared by CNL, April 2016.
(www.ontarioenergyreport.ca)

CNL, 2017. Small Modular Reactor Technology.
(www.cnl.ca/en/home/facilities-and-expertise/smr/default.aspx)

CNL, 2019. “Technology developers advance in CNL’s process to site a small modular reactor,” CNL news release, July 29, 2019.
(www.cnl.ca)

CNSC, 2017. Phase 1 Executive summary – Pre-project design review of Terrestrial Energy Inc. Integral Molten Salt Reactor-400, November 2017.
(www.nuclearsafety.gc.ca/eng/pdfs/Pre-Project_Design_Review/Terrestrial-Energy-Pre-Project-Design-Review-Exec-Summary-eng.pdf)

CNSC, 2019a. Pre-Licensing Vendor Design Review.
(www.nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm)

CNSC, 2019b. Phase 1 Pre-Licensing Vendor Design Review Executive Summary: Ultra Safe Nuclear Corporation, February 2019.
(www.nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/executive-summary-ultra-safe-nuclear-corporation.cfm)

CNSC, 2019c. Phase 1 Pre-Licensing Vendor Design Review Executive Summary: ARC Nuclear Canada Inc., October 2019.
(www.nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/arc-nuclear-canada-executive-summary.cfm)

CNSC, 2019d. Micro Modular Reactor Project.
(www.nuclearsafety.gc.ca/eng/resources/environmental-assessments/ongoing/ontario/EA_80182.cfm)

CNS, 2019. The 9th International Symposium on Supercritical-Water-Cooled Reactors (ISSCWR-9), March 10-14, 2019, Vancouver, Canada.
(www.cns-snc.ca/events/isscwr9)

EASAC, 2014. Management of Spent Nuclear Fuel and its Waste. EASAC policy report # 23, prepared by the European Academies’ Science Advisory Council, July 2014.
(www.easac.eu)

EPRI, 2010. Advanced Nuclear Fuel Cycles – Main Challenges and Strategic Choices. Electric Power Research Institute Report # 1020307, September 2010. United States.
(www.epri.com)

EPRI, 2015. Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design. Electric Power Research Institute Report # 3002005460, October 2015. United States.
(www.epri.com)

EPRI, 2016. Program on Technology Innovation: Assessment of Nuclear Fuel Cycle Simulation Tools. Electric Power Research Institute Report # 3002008044, November 2016. United States.
(www.epri.com)

EPRI, 2017. Program on Technology Innovation: Dynamic Nuclear Fuel Cycle Modeling for Evaluating Liquid-Fueled Molten Salt Reactor Designs. Electric Power Research Institute Report # 3002010474, September 2017. United States.
(www.epri.com)

GENIORS, 2017. Gen IV Integrated Oxide Fuels Recycling Strategies.
(www.geniors.eu)

GIF, 2018. Generation IV International Forum.
(www.gen-4.org)

GFP, 2019a. Licence to Prepare Site Initial Application: MMR Nuclear Plant at Chalk River. Global First Energy Report CRP-LIC-01-002. Global First Energy Document CRP-LIC-01-001, June 2019.
(www.globalfirstpower.com)

GFP, 2019b. Project Description for the Micro Modular Reactor™ Project at Chalk River. Global First Energy Document CRP-LIC-01-001, July 2019.
(www.globalfirstpower.com)

Gobien, 2016. Some Implications of Recycling Used CANDU Fuel in Fast Reactors, paper prepared by M. Gobien, NWMO, presented at 14th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, organized by the OECD NEA, September 6-9, 2016, San Diego, United States.
(www.oecd-nea.org/pt/iempt14)

Government of South Australia, 2016. Royal Commission Report into the Nuclear Fuel Cycle, May 2016.
(yoursay.sa.gov.au/pages/nuclear-fuel-cycle-royal-commission-report-release)

HATCH, 2016. SMR Deployment Feasibility Study – Feasibility of the Potential Deployment of Small Modular Reactors (SMRs) in Ontario, report # H350381-00000-162-066-0001. Prepared by Hatch Ltd., June 2016.
(www.ontarioenergyreport.ca)

IAEA, 2012. Status of Fast Reactor Research and Technology Development. Report # IAEA-TECDOC-1691, prepared by the IAEA, December 2012.
(www.iaea.org)

IAEA, 2013. Design Features and Operating Experience of Experimental Fast Reactors. Report # NP-T-1.9, prepared by the IAEA, November 2013.
(www.iaea.org)

IAEA, 2017a. Research Reactors for the Development of Materials and Fuels for Innovative Nuclear Energy Systems. Report # NP-T-5.8, prepared by the IAEA, September 2017.
(www.iaea.org)

IAEA, 2017b. Use of Low Enriched Uranium Fuel in Accelerator Driven Subcritical Systems. Report # IAEA-TECDOC-1821, prepared by the IAEA, August 2017.
(www.iaea.org)

IAEA, 2018a. Experimental Facilities in Support of Liquid Metal Cooled Fast Reactors. Report # NP-T-1.15, prepared by the IAEA, October 2018.
(www.iaea.org)

IAEA, 2018b. ARIS – Advanced Reactors Information System, database maintained by the IAEA, November 2018.
(aris.iaea.org)

IAEA, 2018c. Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2018 Edition, September 2018.
(aris.iaea.org)

IAEA, 2019a. International Conference on the Management of Spent Fuel from Nuclear Power Reactors: Learning from the Past, Enabling the Future, June 24-28, 2019, Vienna, Austria.
(event.do/iaea/a/#/events/3293)

IAEA, 2019b. Waste from Innovative Types of Reactors and Fuel Cycles. A Preliminary Study. Report # NW-T-1.7, prepared by the IAEA, July 2019.
(www.iaea.org)

ICAPP, 2019. 2019 International Congress on Advances in Nuclear Power Plants, May 12-15, 2019, Juan-les-Pins, France.
(www.sfen-icapp2019.org)

ICENES, 2019. 19th International Conference on Emerging Nuclear Energy Systems, October 6-8, 2019, Bali, Indonesia.
(icenes2019.fmipa-itb.org)

ICONE, 2019. 27th International Conference on Nuclear Engineering, organized by the American Society of Mechanical Engineers, May 19-24, 2019, Tsukuba, Japan.
(www.icone27.org)

INL, 2017. Advanced Fuel Cycle Cost Basis – 2017 Edition. Report # INL/EXT-17-43826, NTRD-FCO-2017-000265 prepared by Idaho National Laboratory for the United States Department of Energy Fuel Cycle Options Campaign, September 2017.
(www.inl.gov)

Ion, 2016. Some Implications of Recycling Used CANDU Fuel in Fast Reactors, paper prepared by M. Ion, NWMO, presented at 3rd Canadian Conference on Nuclear Waste Management, Decommissioning and Environmental Restoration, organized by the Canadian Nuclear Society, September 11-14, 2016, Ottawa, Canada.
(www.nwmder2016.org)

Jackson, 2008. Watching Brief on Reprocessing, Partitioning and Transmutation and Alternative Waste Management Technology – Annual Report 2008. Report prepared for the NWMO by David P. Jackson & Associates Ltd., NWMO TR-2008-22, December 2008.
(www.nwmo.ca)

Jackson, 2009. Watching Brief on Reprocessing, Partitioning and Transmutation (RP&T) and Alternative Waste Management Technology – Annual Report 2009. Report prepared for the NWMO by David P. Jackson & Associates Ltd., NWMO TR-2009-32, December 2009.
(www.nwmo.ca)

Jackson, 2010. Watching Brief on Reprocessing, Partitioning and Transmutation (RP&T) and Alternative Waste Management Technology – Annual Report 2010. Report prepared for the NWMO by David P. Jackson & Associates Ltd., NWMO TR-2010-24, December 2010.
(www.nwmo.ca)

Kessler et al., 2012. “Radiotoxicity Index”: An Inappropriate Discriminator for Advanced Fuel Cycle Technology Selection. Paper # 12276, prepared by John Kessler, Michael Apted, Matthew Kozak, Mark Nutt, Andrew Sowder and Peter Swift at Waste Management 2012 Conference, February 26-March 1, 2012, Phoenix, Arizona.
(www.wmsym.org)

MIIS, 2013. The Bigger Picture: Rethinking Spent Fuel Management in South Korea. James Martin Center for Nonproliferation Studies, Monterey Institute of International Studies, Occasional Paper No. 16, March 2013.
(cns.miis.edu/opapers/pdfs/130301_korean_alternatives_report.pdf)

MIT, 2011. The Future of the Nuclear Fuel Cycle – An Interdisciplinary MIT Study. Massachusetts Institute of Technology, April 2011.
(energy.mit.edu/wp-content/uploads/2011/04/MITEI-The-Future-of-the-Nuclear-Fuel-Cycle.pdf)

MRS, 2019. Materials Research Society's Symposium EN17 – Structure-Property Processing Performance Relationships in Materials for Nuclear Technologies, December 2-5, 2019, Boston, United States.
(www.mrs.org/fall2019/symposium-sessions)

NB Power, 2019. "NB Power Pleased with Progress on Small Modular Reactor Work," New Brunswick Power news release, July 25, 2019.
(www.nbpower.com)

NEI, 2019. 9th Annual International SMR & Advanced Reactor Summit 2019, April 2-3, 2019, Atlanta, United States.
(www.nuclearenergyinsider.com/international-smr-advanced-reactor)

NWMO, 2015a. Some implications of recycling CANDU used fuel in fast reactors, NWMO Technical Report NWMO-TR-2015-11, December 2015.
(www.nwmo.ca)

NWMO, 2015b. Preliminary hazard assessment of waste from an advanced fuel cycle, NWMO Technical Report NWMO-TR-2015-22, December 2015.
(www.nwmo.ca)

NWMO, 2017. Postclosure Safety Assessment in a Used Fuel Repository in Crystalline Rock. NWMO Technical Report NWMO TR-2017-02, December 2017.
(www.nwmo.ca)

NWMO, 2018a. Watching brief on advanced fuel cycles – 2018 update.
(www.nwmo.ca)

NWMO, 2018b. Postclosure Safety Assessment in a Used Fuel Repository in Sedimentary Rock. NWMO Technical Report NWMO-TR-2018-08, December 2018.
(www.nwmo.ca)

NWMO, 2019. Nuclear Fuel Waste Projections in Canada – 2019 Update. NWMO Technical Report NWMO-TR-2019-14, September 2019.
(www.nwmo.ca)

OECD/NEA, 2011. Potential Benefits and Impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation, Report # 6894, prepared by the OECD NEA, September 2011.
(www.oecd-nea.org)

OECD/NEA, 2012a. Homogeneous Versus Heterogeneous Recycling of Transuranics in Fast Nuclear Reactors. Report # 7077, prepared by the OECD NEA, December 2012.
(www.oecd-nea.org)

OECD/NEA, 2012b. Spent Nuclear Fuel Reprocessing Flowsheet. Report # NEA/NSC/WPFC/DOC(2012)15, prepared by the OECD NEA, June 2012.
(www.oecd-nea.org)

OECD/NEA, 2013a. The Economics of the Back End of the Nuclear Fuel Cycle. Report # 7061, prepared by the OECD NEA, September 2013.
(www.oecd-nea.org)

OECD/NEA, 2013b. Transition Towards a Sustainable Nuclear Fuel Cycle. Report # 7133, prepared by the OECD NEA, July 2013.
(www.oecd-nea.org)

OECD/NEA, 2015a. Review of Integral Experiments for Minor Actinide Management, Report # 7222, prepared by the OECD NEA, February 2015.
(www.oecd-nea.org)

OECD/NEA, 2015b. Introduction of Thorium in the Nuclear Fuel Cycle, Report # 7224, prepared by the OECD NEA, June 2015.
(www.oecd-nea.org)

OECD/NEA, 2016. Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment. Report # 7213 prepared by the OECD NEA, September 2016.
(www.oecd-nea.org)

OECD/NEA, 2018. State-of-the-Art Report on the Progress of Nuclear Fuel Cycle Chemistry. Report # 7267 prepared by the OECD NEA, 2018.
(www.oecd-nea.org)

OECD/NEA, 2019a. 4th International Workshop on Technology and Components of Accelerator-Driven Systems (TCADS-4), October 14-17, 2019, Antwerp, Belgium.
(www.oecd-nea.org)

OECD/NEA, 2019b. Proceedings of the Nuclear Energy Agency International Workshop on Chemical Hazards in Fuel Cycle Facilities Nuclear Processing. Workshop organized by OECD NEA, April 17-19, 2018, Boulogne-Billancourt, France. NEA/CSNI/R(2019)9 and NEA/CSNI/R(2019)9/ADD1, May 2019.
(www.oecd-nea.org)

RWM, 2017. Review of Alternative Radioactive Waste Management Options. Report # NDA/RWM/146, prepared by Radioactive Waste Management Ltd., United Kingdom, March 2017.
(www.gov.uk/government/organisations/radioactive-waste-management)

Sandia, 2012. Influence of Nuclear Fuel Cycles on Uncertainty of Geologic Disposal. Report # FCRD-UFD-2012-000088, prepared for the United States Department of Energy Used Fuel Disposition Campaign by Sandia National Laboratories, July 2012.
(www.energy.gov)

SMR (Canadian Small Modular Reactor Roadmap Steering Committee), 2018. A Call to Action: A Canadian Roadmap for Small Modular Reactors.
(smrroadmap.ca/wp-content/uploads/2018/11/SMRroadmap_EN_nov6_Web-1.pdf)

SNETP, 2012. The Sustainable Nuclear Energy Technology Platform – Strategic Research Agenda – Molten Salt Reactors.
(www.snetp.eu)

SNETP, 2015. The Sustainable Nuclear Energy Technology Platform – Deployment Strategy.
(www.snetp.eu)

SNETP, 2018. The Sustainable Nuclear Energy Technology Platform – Advanced Lead Fast Reactor European Demonstrator (ALFRED Project).
(www.snetp.eu)

Triplett et al., 2012. PRISM: A Competitive Small Modular Sodium-Cooled Reactor. Paper by Brian S. Triplett, Eric P. Loewen, and Brett J. Dooies, published in *Nuclear Technology*, vol. 178, May 2012.
(www.gehitachiprism.com)

U.S. BRC, 2012. Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy, January 2012.
(www.energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf)

U.S. NRC, 2012. Environmental Topical Report for Potential Commercial Spent Nuclear Fuel Reprocessing Facilities in the United States – Final Report, September 2012.
(www.nrc.gov)

WNA, 2019. World Nuclear Fuel Cycle Conference, organized by the World Nuclear Association and the Nuclear Energy Institute, April 9-11, 2019, Miami, United States.
(www.wnfc.info)

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