

# Watching brief on advanced fuel cycles and alternative waste management technology

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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 and alternative methods for long-term management of used nuclear fuel. The NWMO's analysis concluded that reprocessing of used fuel was a highly unlikely scenario for Canada at that time. In addition, there were no preferred alternative technical methods. 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 advanced fuel cycles, as well as recent developments in the deep borehole disposal concept. The main conclusions are:

- » There continues to be international interest in new fuel cycles, as well as in the very deep borehole concept, 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 will result in small quantities of new nuclear fuel waste types. The impact of these potential new wastes on the NWMO program is evaluated as part of the consideration of the SMR technologies.
- » Advanced fuel cycles considered to date will produce long-lived nuclear fuel waste that would need to 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 our watching brief on developments on advanced fuel cycles and alternative technical methods 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, as well as alternative technical methods for the long-term management of used nuclear fuel. Previous detailed technical reports [Jackson, 2008-2010] and summary watching brief reports [e.g., NWMO, 2021] are available on the NWMO website.

Research and development work continued in 2022 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), and alternative technical methods for the long-term management of used nuclear fuel.

## 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 reused again. In one version, used fuel is reprocessed to recover plutonium, converted to mixed Pu-U oxide (MOX) fuel and reused once more in a current reactor type (used to some extent in France). In another version, used fuel from a light water reactor (LWR) is considered to be converted into fuel for reuse in a CANDU reactor (planned to be used in China).
- » "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 reactor, additional amounts of natural or depleted uranium or reprocessed used fuel can be added to replenish the fuel consumed in the FR.

Other variations can include combinations of conventional thermal reactors, FRs and/or accelerator-driven systems (ADS).

The majority of the commercial nuclear power reactors in operation around the world today are based on thermal (“low energy”) neutrons. These reactors use a moderator material to slow down the high energy neutrons from the fission reactions – the 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 and 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, the depleted uranium from the enrichment process is a potential fuel source for some advanced reactor fuel cycles.

A closed fuel cycle requires a FR in order to effectively use the fuel. FRs do not use a moderator, and FR technology is more complicated. Table 1 lists the currently operating or planned FRs for generating electricity. They can extract energy from U-238, as well as other actinides (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. Depleted uranium 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.

**Table 1: Fast reactors currently in operation or under construction for generating electricity**

Country	Facility	Capacity (MWe)	Status
Russian Federation	BN-600 BN-800	600 880	Operating since 1980 – sodium pool type Operating since 2016 – sodium pool type
India	PFBR	500	Under construction – sodium pool type
China	CFR-600	2 x 600	Under construction – sodium pool type

Canada, as well as most other nuclear power generating countries, currently follows the open fuel cycle. As shown in Table 2, a few countries, notably France, the Russian Federation 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; their reprocessed fuel is being treated as waste. Table 3 shows a summary of global reprocessing capacity for commercial fuels, not including smaller and already closed facilities and facilities used solely for military purposes. It also includes information on the nuclear fuel cycle strategies for countries using CANDU fuel.

Table 2: 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				✓	✓
Bulgaria			✓	✓ <sup>(7)</sup>	
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>	✓	✓			
Italy			✓		
Japan		✓ <sup>(6)</sup>	✓		
Korea, Rep. of					✓
Mexico					✓
Netherlands			✓ <sup>(5)</sup>		
Pakistan <sup>(3)</sup>					
Romania					✓
Russian Federation <sup>(3)</sup>	✓	✓			
Slovakia				✓ <sup>(7)</sup>	✓
Slovenia					✓
Spain				✓	✓
Sweden				✓	✓
Switzerland				✓	✓
Ukraine				✓ <sup>(7)</sup>	✓
United Kingdom <sup>(1)</sup>				✓	✓
United States <sup>(3)</sup>				✓	✓

(1) The United Kingdom ceased all reprocessing in July 2022.

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

(3) China, France, the United Kingdom, the 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. Contract extended in 2015 to end of life for current reactors.

(6) Commercial scale facility at Rokkasho-mura has been constructed and is undergoing final commissioning test.

(7) Some used fuel was sent to former Soviet Union for reprocessing. Practice terminated in early 1990s.

Table 3: Summary of global reprocessing capacity for commercial fuels

Country	Facility	Capacity (tonnes per year)	Status
China	Gansu	200	Under construction (expected ~2025)
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	Tarapur	100	In operation
	Kalpakkam	100	In operation
Japan	Tokai	90	Shut down/decommissioning
	Rokkasho	800	In commissioning (expected ~2024)
Russian Federation	RT-1, Mayak	400	In operation (expected shut down ~2030)
	MCC-PDC	250	Under construction
	RT-2, Zheleznogorsk	700	Under construction (expected ~2025)
United Kingdom	MAGNOX, Sellafield	1,500	Shut down 2022
	THORP, Sellafield	900	Shut down 2018
United States	West Valley	300	Operated 1966-72, decommissioned

## Advanced fuel cycles

The primary interest in advanced fuel cycles is with respect to closed fuel cycles (although partial fuel cycles are currently in limited use). Such 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.

Reducing the need for fresh uranium is the direct benefit. For Canada, with significant uranium resources, this would reduce environmental impact of mining through efficient use of the mined uranium.

A second potential benefit is to reduce the “radiotoxicity” of the waste. This would be achieved by reprocessing the fuel and recycling some or most of the actinides, i.e., uranium and transuranics, into a FR. The actinides are typically long-lived, so consuming them in a FR reduces the burden on the repository needed to handle the remaining long-lived wastes.

A third potential benefit is to reduce the size of the repository by reducing the waste volume, or equivalently to allow one repository to handle a larger nuclear fleet. Uranium constitutes the bulk of the used fuel, so separating and reusing it removes waste volume.

However, there are scientific and engineering challenges with advanced fuel cycles such as development of suitable materials, and the scale up from experiments to full-sized reactors. There are also economic and socio-political challenges, including the costs for development and siting of facilities, and addressing the risk of proliferation. Achieving these benefits assumes that nuclear energy continues to be an economic choice for a given country.

With respect to repository size, recycling of used fuel into FRs can reduce the volume of high-level waste produced per megawatt of electricity generated. This could reduce the amount of repository rock that needs to be excavated per megawatt, but 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 nor by its volume per megawatt. The thermal output of the wastes is primarily driven by how much power has been produced regardless of the fuel cycle. In order to achieve significant reduction in repository footprint, there would also need to be partitioning of the shorter-lived fission products, plus significant duration surface storage for decay of heat generating radionuclides. Even in this case, the reduction in high-level waste repository space may be offset by the increase in the long-lived intermediate-level wastes resulting from these fuel cycles [RED-IMPACT, 2008].

Also, reducing the actinides does not avoid the need for some long-term waste management due to residual actinides and the long-lived fission products. While reducing the long-lived actinides reduces the “radiotoxicity” of the waste and is clearly favorable, it may not significantly improve the overall safety of a repository because the actinide elements have very low mobility in the repository environment. It is the long-lived fission products, such as I-129, that are generally the key radionuclides driving the repository long-term safety [Kessler et al., 2012; Sandia, 2012a; Posiva, 2021; EASAC, 2014; NWMO, 2017, 2018]. These long-lived fission products are generally not reduced in advanced fuel cycles. Furthermore, recycling fuel to generate more electricity means that there will be more fission products produced, approximately proportional to the total power generated, regardless of fuel cycle.

In any event, fully implementing a closed fuel cycle requires the commercial scale deployment of advanced reactors such as FRs, 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 Table 1). See, for example, [IAEA, 2012, 2013, 2022d] for descriptions of various FR prototypes and their operating histories.

These factors have been reflected in various national reviews, which have continued to support the need for a deep geological repository for used nuclear fuel or high-level wastes. In particular:

- » 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” [MIIIS, 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].
- » The Nuclear Energy Agency (NEA) has stated in its Policy Brief on the disposal of radioactive waste issued in June 2020 that “there is a strong international scientific consensus that deep geological repositories (DGRs) are a safe and effective approach to the permanent disposal of high-level wastes and spent nuclear fuel” [OECD/NEA, 2020a].
- » A recent study in the United States on the merits and viability of different nuclear fuel cycles using advanced reactors, conducted by the National Academies of Sciences, Engineering and Medicine stated that “Most importantly, advanced reactors and their associated fuel cycles would not eliminate the requirement for geologic repositories for some radioactive wastes because even advanced reactors will require disposal of radioactive fission products” [NASEM, 2022].

## Technology status for advanced fuel cycles

There continues to be interest in advanced fuel cycles, and progress is being made in the underlying science and technology. Most recent findings were presented in 2022 at various international conferences and technical meetings held in person and virtually, notably:

- » 11<sup>th</sup> International SMR & Advanced Reactor Summit 2022 (May 2022, Atlanta, United States) [Reuters Events, 2022];
- » GLOBAL 2022 International Conference on Nuclear Fuel Cycle, New Nuclear Perspectives in the Energy Supply Crisis and Climate Emergency (July 2022, Reims, France) [SFEN, 2022];
- » 29<sup>th</sup> International Conference on Nuclear Engineering, ICONE29 (August 2022, Shenzhen, China) [ICONE, 2022];
- » World Nuclear Association Symposium (September 2022, London, United Kingdom) [WNA, 2022a];
- » TopFuel 2022 (October 2022, Raleigh, United States) [ANS, 2022];
- » GEN IV International Forum (October 2022, Toronto, Canada) [GIF, 2022a];
- » Canadian Nuclear Society's 4<sup>th</sup> International Conference on Generation IV and Small Reactors (G4SR-4) (October 2022, Toronto, Canada) [CNS, 2022]; and
- » Materials Research Society's Symposium, EN08-Scientific Basis for Nuclear Waste Management (November-December 2022, Boston, United States) [MRS, 2022].

The NWMO monitors these conferences, as well as technical reports published by the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA) [e.g., OECD/NEA, 2011-2021c], International Atomic Energy Agency (IAEA) [e.g., IAEA, 2012-2022e], 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, 2015-2021], the United Kingdom Radioactive Waste Management agency [RWM, 2017], and various international collaborative projects (such as the European Sustainable Nuclear Energy Technology Platform [SNETP, 2012-2021], the Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution [ASGARD, 2016], and the GEN IV Integrated Oxide Fuels Recycling Strategies [GENIORS, 2020] projects).

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

## Discussion on advanced reactors

Advanced fuel cycles are generally considered in the context of particular reactor concepts, as the reprocessing approach is closely related to the reactor concept.

Work on advanced reactor concepts can be loosely characterized as Generation III+ or Generation IV (GEN-IV), where current commercial power reactors now under construction are considered as Generation III. There is an international GEN-IV collaborative project which is considering several designs, including both thermal reactors and FRs [GIF, 2022b] [IAEA, 2019, 2022d, 2022e]. These advanced reactor concepts typically operate at very high temperatures (typically 400°C or more), and use liquid metals (e.g., sodium or lead), molten salts (e.g., fluoride or chloride mixtures), or gases (helium) as coolants rather than light water or heavy water.

In addition, SMRs have also gained a lot of international interest. The focus of these is on small power output, allowing them to be built in a more modular manner, at lower cost, and potentially used in more places than the conventional 1,000 MWe power reactors. These SMR concepts include both small versions of conventional thermal reactors, as well as FRs.

While there are a large number of SMR concepts that have been proposed worldwide [IAEA, 2022d], the concepts described in Table 4 are currently under consideration in Canada and are at different stages of the Canadian Nuclear Safety Commission's (CNSC) vendor design review. In addition to the SMRs included in Table 4, two vendors (Westinghouse Electric Company, LLC and StarCore Nuclear) have also applied for service agreements with the CNSC to conduct evaluations of their concept designs (eVinci Micro Reactor solid core and heat pipes, and StarCore module high-temperature gas, respectively) [CNSC, 2022].

**Table 4: SMRs currently under evaluation in Canada**

Reactor	Vendor	Fuel/Coolant	Type	CNSC vendor design review status [CNSC, 2022]
ARC-100	ARC Nuclear Canada Inc.	Metal/Liquid sodium	Fast reactor	Phase 1 complete Phase 2 in progress
MMR-5, MMR-10	Ultra Safe Nuclear Corporation	Coated oxide in SiC pellet/Helium	Thermal reactor	Phase 1 complete Phase 2 in progress Global First Power submitted application for licence to prepare site
SSR	Moltex Energy	Molten salt/ Molten salt	Fast reactor	Phase 1 complete
IMSR	Terrestrial Energy Inc.	Molten salt/ Molten salt	Thermal reactor	Phase 1 complete Phase 2 in progress
Xe-100	X-energy, LLC	Coated oxide in graphite pebble/Helium	Thermal reactor	Phase 2 in progress
BWRX-300	GE-Hitachi Nuclear Energy	UO <sub>2</sub> /Light water	Thermal reactor	Phase 2 in progress BWRX-300 was selected by OPG for deployment at Darlington site
SMR-160	SMR, LLC (A Holtec International Company)	UO <sub>2</sub> /Light water	Thermal reactor	Phase 1 complete
NuScale	NuScale Power, LLC	UO <sub>2</sub> /Light water	Thermal reactor	Phase 2 in progress

In 2020, the Government of Canada has launched Canada's SMR Action Plan, which outlines Canada's plan for development, demonstration and deployment of SMRs for various applications [SMR Action Plan, 2020]. A memorandum of understanding was signed in 2019 between governments of Ontario, Saskatchewan and New Brunswick on collaborating on the development and deployment of SMRs in these provinces. Alberta signed the memorandum of understanding in 2021.



A number of utilities have expressed interest in supporting the development of SMR technologies. A feasibility report, prepared by Ontario Power Generation (OPG), Bruce Power, NB Power and SaskPower, was published in 2021, providing a feasibility assessment of SMR development and deployment in each of the three provinces [OPG, Bruce Power, NB Power and SaskPower, 2021].

OPG resumed in 2020 the planning activities at the Darlington site for hosting a grid-size SMR [OPG, 2020]. In December 2021, OPG announced that it will work together with GE Hitachi Nuclear Energy to deploy a BWRX-300 SMR at the Darlington new nuclear site, which is the only site currently licensed in Canada for new nuclear build [OPG, 2021]. OPG intends to begin non-nuclear site preparation activities for an SMR at Darlington by the end of 2022 and submitted an application to the CNSC for the Licence to Construct in October 2022 [OPG, 2022].

In 2019, Global First Power, Ultra Safe Nuclear Corporation and OPG formed a joint venture to own and operate the Micro Modular Reactor Project at Chalk River [GFP, 2020a]. Global First Power submitted to the CNSC the initial application for a Licence to Prepare Site, and the regulatory review is underway [GFP, 2019a, 2019b]. In 2022, McMaster University, Ultra Safe Nuclear Corporation and Global First Power formed a partnership and signed a Memorandum of Understanding to study the feasibility of deploying a Micro Modular Reactor at McMaster University or an affiliated site [USNC, 2022].

New Brunswick Power is working with Moltex Energy and Advanced Reactor Concepts (ARC) Clean Energy Canada for developing and demonstrating an advanced SMR nuclear energy research cluster [NB Power, 2019].

SaskPower has selected in June 2022 the GE Hitachi Nuclear BWRX-300 SMR for potential deployment in the province [SaskPower, 2022a]. In September 2022, SaskPower identified two areas in Saskatchewan for further study to determine the feasibility of hosting a SMR [SaskPower, 2022b].

Bruce Power and Westinghouse announced an agreement to pursue applications of Westinghouse's proposed eVinci™ micro reactor program within Canada [Bruce Power, 2020]. Bruce Power has also committed to the development of SMR technology, including memorandums of understanding with MIRARCO Mining Innovation and Laurentian University [Bruce Power, 2018a], as well as NuScale Power [Bruce Power, 2018b].

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; GFP, 2020b]. CNL has also formed partnerships with SMR vendors to research SMR fuels and advance SMR technology in Canada [CNL, 2020a, 2020b, 2020c, 2020d]. CNL recently issued a call for proposals for the third round of its Canadian Nuclear Research Initiative (CNRI) program, which was established to accelerate the deployment of SMRs and advanced reactors, including SMR design concepts [CNL, 2021].

In 2021, a report was published by the Canadian Standards Association on the role of standards in facilitating deployment of SMRs in Canada [CSA, 2021].

The FR SMR concepts under advanced consideration use metal or salt fuels; the ARC fuel could be U-Zr metal, and the Moltex fuel could be a sodium/plutonium/actinide-chloride or -fluoride mix. The thermal reactor SMR concepts use a uranium-fluoride-based salt as both fuel and coolant (Terrestrial Energy), coated UO<sub>2</sub> encased in SiC pellets (Ultra Safe Nuclear Corporation), coated UO<sub>2</sub> or UC embedded in graphite pebbles (X-energy), or UO<sub>2</sub> (BWRX-300, SMR-160, NuScale). For comparison, current CANDU fuel is UO<sub>2</sub>.

## Discussion on reprocessing

Advanced fuel cycles require some type of reprocessing. The current commercial reprocessing technology as used in the facilities listed in Table 1 is based on oxide fuels and wet chemistry (the “PUREX” process). The  $UO_2$  used fuel is dissolved in concentrated acids, then subject to a series of chemical steps to separate out (partition) the various constituents. Relatively pure Pu is separated and converted into an oxide that can be mixed with fresh  $UO_2$  to form MOX fuel, which can be reused again in a conventional thermal reactor. Descriptions of the process used can be found in the technical literature, such as [OECD/NEA, 2012b].

Since the used nuclear fuel is highly radioactive, all this needs to be done using remotely operated, heavily shielded equipment and facilities. 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 secondary radioactive waste that must be stabilized for storage, then ultimately placed in a repository [MIT, 2011; MIRS, 2013].

This is the benchmark for fuel reprocessing and is a relatively expensive process. Some of the ongoing research is aimed at optimizing this process. Two primary options have been under development – hydrometallurgical and electrometallurgical processes. The hydrometallurgical partitioning, also known as solvent extraction process, builds on the current industrial experience. The electrometallurgical or pyroprocessing concept is a non-aqueous approach. Another concept that is less developed is the fluoride volatility process.

The pyroprocessing approach is suitable for metallic and salt fuel. This approach 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] and the ARC SMR [Cheng et al., 2018]. While successfully used in demonstration tests, pyroprocessing has not yet achieved commercial scale implementation. (See, for example, [IAEA, 2021], and Iizuka et al. in [OECD/NEA, 2012a].) Korea had been conducting studies for demonstration at laboratory and engineering scale [OECD/NEA, 2019c].

Moltex Energy proposes to use a form of pyroprocessing, called WATSS (Waste To Stable Salts), to convert spent oxide fuel to a salt form suitable for its Stable Salt Reactor (SSR). A particular feature of its SSR concept is that it is more tolerant of actinides present in the fuel, which means that the reprocessing does not need to deliver a highly purified product, which in turn simplifies the design. Currently, research and planning for development and inactive demonstration of the WATSS process is underway.

In order to be successfully deployed on a commercial basis, the life cycle cost of producing electricity with advanced reactors and reprocessing 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 that 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, in support of 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] 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.

Many of the studies point out that as an alternative to reprocessing the used nuclear fuel from current reactors, there is sufficient depleted uranium available (from LWR fuel enrichment) to sustain advanced reactors globally for many centuries. This uranium is relatively low radioactivity and easier to handle. About 1.2 million tonnes of depleted uranium are currently stockpiled around the world. Also, the use of enriched uranium could substitute for recycled plutonium at least in the short term [WNA, 2022b].

## Discussion on transmutation

The transmutation of actinides into less radioactive or stable elements 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 nuclear reactor, this is a sub-critical system: the nuclear reaction stops when the accelerator is turned off. An alternative proposal uses a high-power, short-pulse laser as the particle accelerator. An ADS can potentially accept a wide isotopic mix in the blanket assembly, providing very efficient transmutation of actinides and some other long-lived radionuclides.

Significant electrical power is required to generate the neutrons. Some research is underway in Europe, Japan and elsewhere to develop ADS technology. 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 4<sup>th</sup> International Workshop on Technology and Components of Accelerator-Driven Systems [OECD/NEA, 2019a].

## Very deep borehole disposal

A proposed alternative waste management approach is placing the used fuel in very deep boreholes. The concept consists of placing the waste containers at depths greater than 1 kilometre in individual boreholes drilled from the surface. Within each borehole, waste packages would be stacked on top of each other over some distance. With the waste in place, the borehole would be backfilled and sealed to the surface. With the waste placed at this depth, further away from the biosphere than in the mined repository concept, the long-term safety of the system would rest primarily on the separation of the hydrogeological regime at the depth of the waste packages from that near the surface, and on the integrity of the borehole plugs and seals.

To date, a number of studies have suggested that very deep boreholes could potentially have a number of technical advantages compared to mined geologic repositories for certain high-level waste types, such as potential for greater isolation of waste and reduced mobility of radionuclides by increasing the depth, as well as modularity because the disposal capacity can be expanded relatively easily by drilling additional boreholes once a suitable area has been identified and licensed.

The very deep borehole concept has been studied as an alternative to mined deep geological repositories in the United States [Sandia, 2009-2019; U.S. BRC, 2012; U.S. NWTRB, 2016; Deep Isolation, 2020], Sweden [SKB, 1989-2013c; KASAM, 2007], the United Kingdom [NIREX, 2004], and elsewhere [von Hippel and Hayes, 2010; Chapman, 2013]. A 2020 study by the Electric Power Research Institute investigated the feasibility of co-locating a deep borehole disposal with an advanced reactor located on the same site in the United States [EPRI, 2020].

The concept of very deep boreholes is considered for underground disposal of small inventories of intermediate- and high-level radioactive waste [IAEA, 2017c, 2020d; ARPANSA, 2008]. Australia is presently considering borehole disposal for intermediate-level waste [ARPANSA, 2020], and Estonia and Slovenia are considering the concept for disposal of used fuel from SMRs and research reactors, respectively [WNN, 2021a, 2021b].

The United States Department of Energy (U.S. DOE) began studies in 2009 on the very deep borehole concept for disposal of spent fuel assemblies from U.S. nuclear power reactors. Initial studies published by Sandia National Laboratories presented a preliminary evaluation of the concept [Sandia, 2009] and a reference design [Sandia, 2011a,b]. In this design, the waste is assumed to be placed in the lower 1- to 2-kilometre portion of an approximately 3- to 5-kilometre deep borehole, about 45 centimetres in diameter, vertically drilled through overlying rock into crystalline basement rock. Although retrievability would be maintained during placement operations, retrievability of the waste after borehole sealing is assumed not to be required.

In 2014, the U.S. DOE initiated a project to drill a test deep borehole to evaluate the technology for specific types of small-sized, high-activity wastes (such as concentrated Cs and Sr capsules currently stored on the Hanford site) [Sandia, 2014b; U.S. DOE, 2014a,b; U.S. NWTRB, 2016]. The Deep Borehole Field Test Program involved the design, siting and construction of at least one full-sized, non-radioactive deep borehole to a depth of 5 kilometres [Sandia, 2012c, 2015a,b]. A preliminary generic safety case was developed, supporting the feasibility of the concept for disposal of Cs and Sr capsules [Sandia, 2016, 2019]. In 2016, the U.S. DOE announced that a 20-acre site on state-owned land near Rugby, North Dakota, was the preferred site [U.S. DOE, 2016]. However, even though the proposal did not involve the actual disposal of radioactive waste, it was met with extensive local opposition, and a drilling licence was not issued. The project was discontinued in 2017 [U.S. DOE, 2017].

An alternative concept has also been proposed based on disposal of radioactive waste in less deep horizontal boreholes, to potentially impose less stress on the waste packages and allow retrievability. The concept consists of a borehole that would be drilled vertically from the surface, through the sedimentary, igneous or metamorphic rock, to a depth of about 1 kilometre, after which the borehole would then be turned sub-horizontal [Deep Isolation, 2020]. Several long, sub-horizontal boreholes would be used to contain the radioactive waste packages. A private nuclear waste disposal company in the United States, Deep Isolation, proposes to use existing directional drilling technologies, and performed in 2019 a public demonstration test of this concept by placing and retrieving a prototype canister from an existing deep horizontal borehole at about 600 metres underground [Deep Isolation, 2019].

While the concept of very deep disposal for used fuel is considered to be technically feasible, there are some significant challenges to the approach, such as:

- » Drilling of boreholes of the required diameter to the required depth;
- » Controlled emplacement of waste packages at depth (e.g., engineering challenges regarding the limitations of the sizes of the used fuel containers/packages, as well as challenges concerning how to recover if a package gets “stuck” in the borehole before it reaches the intended depth);
- » Development of robust monitoring technology over an extensive area and depth;
- » Development of reliable borehole seals that can be remotely placed from surface; and
- » After waste packages are sealed in place, retrieval would be very difficult.

Overall, the United States Nuclear Waste Technical Review Board [U.S. NWTRB, 2016] concluded that even if deep boreholes proved feasible for certain waste types, they will not eliminate the need for a conventional mined geologic repository. In addition, they concluded that the time required to site, license and develop a deep borehole disposal facility would be comparable to that needed for a conventional mined repository.

The NWMO will continue to monitor the deep boreholes concept as part of our ongoing review of the APM approach.

## Conclusions

The NWMO continues to monitor developments in the area of advanced fuel cycles and alternative methods for long-term waste management.

The main conclusions from the NWMO perspective are:

- » There continues to be international interest in new fuel cycles, as well as in the very deep borehole concept, 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 will result in small quantities of new nuclear fuel waste types. The impact of these potential new wastes on the NWMO program is evaluated as part of the consideration of the SMR technologies.
- » Advanced fuel cycles considered to date will produce long-lived nuclear fuel waste that would need to 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 our watching brief on developments on advanced fuel cycles and alternative technical methods that could have an impact on Canada's future waste management requirements.

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