NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

(2024 update)

Watching brief on advanced fuel cycles and alternative waste management technology

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 deep borehole disposal concepts. The main conclusions are:

- There continues to be international interest 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 will result in relatively 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.
- There also continues to be international interest in deep borehole concepts. In Canada, the deep geological repository disposal concept and regulations have been developed over decades and discussed with potential host communities, and in 2024, a host site was selected based upon the deep geological repository concept. At this stage in the project, there does not appear to be any major benefits to shift disposal concept from mined deep geological repository to deep borehole disposal (horizontal or vertical).
- 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 watching briefs [e.g., NWMO, 2024] are available on the NWMO website.

Research and development work continued in 2024 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, 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 Canada Deuterium Uranium (CANDU) reactor (studied for potential use 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 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 recovered fuel. FR technology is more complicated than thermal reactors, and therefore, few have been built to date. Table 1 [IAEA, 2024a] 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.). 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 BREST-OD-300	600 885 320	Operating since 1980 – sodium pool type Operating since 2015 – sodium pool type Under construction – lead cooled 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, 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 [IAEA, 2022a]. Recently, France announced plans to increase the use of MOX fuel and reprocessed Uranium fuel (RepU) in French reactors with a new MOX fuel production plant and extended life of the existing reprocessing plant at La Hague [WNN, 2024a, 2024b].

France, Russian Federation and India, despite implementing partially closed fuel cycles, are still planning deep geological repositories for the separated fission-products-containing high-level waste resulting from fuel reprocessing.

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, produced from the International Atomic Energy Agency's (IAEA) Nuclear Fuel Cycle Facilities Database [IAEA, 2024b], 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			
Argentina					✓
Belgium				✓	✓
Bulgaria			✓	✓ [6]	
Canada					✓
China[2]		✓			✓ [3]
Czech Republic				✓ [6]	✓
Finland				✓ [6]	✓
France[2]	✓ [1]				
Germany				✓	✓
Hungary				✓ [6]	✓
India[2]	✓	✓			
Italy				✓	
Japan		✓ [5]	✓		
Korea, Rep. of					✓
Lithuania					✓
Mexico					✓
Netherlands			✓ [4]		
Pakistan[2]					
Romania					✓
Russian Federation[2]	✓	✓			
Slovakia				✓ [6]	✓
Slovenia					✓
Spain				✓	✓
Sweden				✓	✓
Switzerland				✓	✓
Turkey					✓
Ukraine[7]				✓ [6]	✓
United Kingdom[2]				✓	✓
United States[2]				✓	✓

(1) France supplied commercial reprocessing services to a number of European and Asian countries.
(2) 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.
(3) The main policy in China is domestic reprocessing. However, some fuel, mainly from CANDU reactors, is planned for direct disposal.
(4) Used fuel sent to France for reprocessing. Contract extended in 2015 to end of life for current reactors.
(5) Commercial scale facility at Rokkasho-mura has been constructed and is undergoing final commissioning test.
(6) Some used fuel was sent to former Soviet Union for reprocessing. Practice terminated in early 1990s.
(7) Some spent fuel was sent to the Russian Federation for reprocessing. Other fuel is stored awaiting a final decision.

Table 3: Summary of global reprocessing capacity for commercial fuels

Country	Facility	Capacity (tonnes heavy metal per year)	Status
China	Gansu	200	Under construction (expected ~2025)
France	UP1, Marcoule UP2-400, La Hague UP2-800, La Hague UP3, La Hague	600 400 1,000 1,000	Shut down 1997, to be decommissioned Shut down 2004, to be decommissioned In operation In operation
India	Tarapur Kalpakkam	100 100	In operation and planned Integrated Nuclear Recycle Plant expansion under construction In operation
Japan	Tokai Rokkasho	90 800	Shut down 2006, to be decommissioned In commissioning (expected ~2026)
Russian Federation	RT-1, Mayak MCC-PDC, Zheleznogorsk RT-2, Zheleznogorsk	400 250 800	In operation (expected shut down ~2030) Under construction Under construction (expected ~2035)
United Kingdom	MAGNOX, Sellafield THORP, Sellafield	1,500 900	Shut down 2022, to be decommissioned Shut down 2018, to be decommissioned
United States	West Valley Barnwell GE Morris	300 1,500 300	Shut down 1972, to be decommissioned Shut down 1983 (never operated), to be decommissioned Shut down 1971 (never operated), to be decommissioned

Advanced fuel cycles

A primary interest in advanced fuel cycles is with respect to closed fuel cycles. Such closed fuel cycles are of interest because they use the uranium fuel very efficiently. In particular, some closed 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 closed 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 the benefits also 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 unit energy of electricity generated. This could reduce the amount of repository rock that needs to be excavated per unit energy generated, 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 unit energy generated. The thermal output of the wastes is primarily driven by how much energy has been produced, regardless of the fuel cycle. In order to achieve significant reduction in repository footprint, there would also need to be significant duration surface storage for decay of heat generating radionuclides.

A 2021 investigation over a range of fuel cycle scenarios concluded that there is no benefit to the radiotoxic or thermal impact on a deep geological repository from a closed fuel cycle unless the reprocessed FR fuel wastes are stored for longer than 30 years. After 100 years, interim storage total thermal output per unit energy is reduced by approximately one third compared to the once-through fuel cycle of same age, reaching an order of magnitude less at 200 years [Dungan et al., 2021].

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 [Andra, 2016; Posiva, 2021; EASAC, 2014; NWMO, 2017, 2018]. These long-lived fission products are generally not reduced in closed fuel cycles; fission products are produced approximately proportional to the total power generated, regardless of fuel cycle. Additionally, implementation of a closed fuel cycle could result in some mobile fission products (such as I-129) being released into the surface environment during reprocessing operations [OECD/NEA, 2022b].

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; OECD/NEA, 2024] for descriptions of various FR prototypes and their operating histories.

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

- The Nuclear Energy Agency (NEA) has stated in its Policy Brief on the disposal of radioactive waste issued in June 2020 and in its SMR Dashboard that "there is a strong international scientific consensus that deep geological repositories 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, 2023].
- A recent study by the Electric Power Research Institute (EPRI) [EPRI, 2023] analyzed the impact of deploying reprocessing and advanced fuel cycles to national nuclear programmes. Results included that for an advanced fuel cycle to deplete the overall transuranic inventory by 90 per cent compared to an open fuel cycle, it would take over 600 years of continuous operation; and for a reduction of 95 per cent, 1,300 years of continuous operation. The EPRI stated that "The waste management benefits of switching to advanced fuel technologies are secondary, and that advanced fuel cycles are not needed for safe disposal of used fuel and high-level waste."

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 2024 at various international conferences and technical meetings held in person and virtually, notably:

- 5th International Conference on Generation IV and Small Reactors [G4SR-5, 2024] (October 2024, Ottawa, Canada);
- 31st International Conference on Nuclear Engineering, ICONE31 (August 2024, Prague, Czech Republic) [ICONE, 2024], which discussed nuclear plant design and fuel properties;
- World Nuclear Association Symposium 2024 (September 2024, London, United Kingdom) [WNA, 2024], which discussed the increase in nuclear energy capacity, fuel supply and nuclear advances;
- Nuclear Energy Summit 2024 (March 2024, Brussels, Belgium) [IAEA, 2024c], which discussed the nuclear energy's role in achieving global sustainability and energy security goals; and
- European Sustainable Nuclear Energy Technology Platform (SNETP), SNETP Forum 2024 (April 2024) [SNETP, 2024].

The NWMO monitors these conferences, as well as technical reports published by international organizations such as the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA) [e.g., OECD/NEA, 2015-2024], IAEA [e.g., IAEA, 2012-2023b], French Commissariat à l'énergie atomique et aux énergies alternatives (CEA) [e.g., CEA, 2015], United States Department of Energy (U.S. DOE) [U.S. DOE, 2023], EPRI [e.g., EPRI, 2015-2023], the United Kingdom Radioactive Waste Management agency (now known as Nuclear Waste Services (NWS)) [RWM, 2017], and the European SNETP [SNETP, 2015-2023].

In addition to the present annual watching brief, the NWMO has previously prepared technical reports and related conference papers on potential impacts of advanced fuel cycles on Canadian used fuel inventories and long-term management needs [NWMO, 2015a, 2015b; Ion and Gobien, 2016; Gobien and Ion, 2016]. In 2024, the NWMO presented at the G4SR-5 conference preliminary data requirements for safety assessment basis of SMR used fuel waste [Reilly and Gierszewski, 2024].

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, 2023; IAEA, 2019, 2022d, 2023a, 2024a]. These advanced reactor concepts typically operate at very high temperatures (typically 400ºC 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.

It is however noted in research by the U.S. DOE [U.S. DOE, 2023] that cost savings of new SMR designs are expected to only be realized when multiple reactors of the same type are constructed to reach Nth-of-a-kind costs.

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 [CNSC, 2024].

Table 4: Advanced reactors currently under evaluation in Canada

Reactor	Vendor	Fuel/Coolant	Type	CNSC vendor design review and licensing status [CNSC, 2024]
ARC-100	ARC Nuclear Canada Inc.	Metal/Liquid sodium	Fast reactor	Phase 1 complete Phase 2 in progress ARC/NB Power submitted application for licence to prepare site
MMR	Ultra Safe Nuclear Corporation	Coated oxide in SiC pellet/Helium	Thermal reactor	Phase 1 complete Phase 2 on hold
SSR-W300	Moltex Energy	Molten salt/ Molten salt	Fast reactor	Phase 1 complete
IMSR400	Terrestrial Energy Inc.	Molten salt/ Molten salt	Thermal reactor	Phase 1 complete Phase 2 complete
Xe-100	X-energy, LLC	Coated oxide in graphite pebble/Helium	Thermal reactor	Phase 1 complete Phase 2 complete
BWRX-300	GE-Hitachi Nuclear Energy	UO_2/Light water	Thermal reactor	Phase 1 complete Phase 2 complete OPG submitted application for licence to construct at Darlington site
eVinci™	Westinghouse Electric Company, LLC	Coated oxide pebble in graphite block/Heat pipe	Thermal reactor	Phase 1 in progress Phase 2 in progress
CANDU MONARK	Candu Energy Inc.	UO_2/Heavy water	Thermal reactor	Planning 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]. Building on the utilities' feasibility study, the Governments of Ontario, New Brunswick, Saskatchewan and Alberta have developed an interprovincial strategic plan for the deployment of SMRs [Ontario, New Brunswick, Alberta and Saskatchewan, 2023]. The strategic plan includes three streams of SMR deployment:

- Stream 1 – A grid-scale SMR project of 300 MWe constructed at the Darlington nuclear site in Ontario, followed by up to four units in Saskatchewan;
- Stream 2 – Two fourth generation advanced SMRs constructed at the Point Lepreau nuclear site in New Brunswick; and
- Stream 3 – A new class of micro-SMRs designed primarily to replace the use of diesel in remote communities and mines.

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 [OPG, 2021]. OPG started non-nuclear site preparation activities in September 2022 and submitted an application to the CNSC for the Licence to Construct in October 2022 [OPG, 2022]. On July 7, 2023, the Ontario government announced it is working with OPG to commence planning and licensing for three additional SMRs, for a total of four, at the Darlington nuclear site [Ontario, 2023a].

In July 2023, the Ontario government announced it is starting pre-development work with Bruce Power to site a new large reactor project [Ontario, 2023b]. Bruce Power has submitted to the Impact Assessment Agency of Canada an Initial Project Description for expansion of the Bruce Power site for up to 4,800 MWe [Bruce Power, 2024]. The Bruce C project is considering several reactor design options, including light water or heavy water moderated thermal reactors with UO_2 fuel, all with open fuel cycle concepts [Bruce Power, 2024].

In April 2019, GFP submitted to the CNSC an initial application for a Licence to Prepare Site for a SMR at the Chalk River site [GFP, 2019] and followed up with the submission of Part 1 of the full application in July 2023 [GFP, 2023]. In October 2024, Ultra Safe Nuclear Corporation (USNC) announced that it is seeking to run a sale process pursuant to Section 363 of Chapter 11 of the United States Bankruptcy Code. During this process, USNC will maintain operational continuity across its projects, including the deployment of its Micro Modular Reactor (MMR) systems in the United States and Canada [USNC, 2024]. At the time of writing this document, the CNSC review of GFP's application was still in progress.

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]. On June 30, 2023, NB Power submitted an Environmental Impact Assessment registration document to the Department of Environment and Local Government [New Brunswick, 2023] and a Licence to Prepare Site application to the CNSC [NB Power, 2023].

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]. In November 2023, the Government of Saskatchewan announced $80 million for the Saskatchewan Research Council to pursue the deployment of an eVinci™ micro reactor, which will be built by Westinghouse Electric Company and expected to be operational by 2029 [Saskatchewan, 2023].

Bruce Power and Westinghouse announced an agreement to pursue applications of Westinghouse's proposed eVinci™ micro reactor program within Canada [Bruce Power, 2020]. Additionally, 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].

Canadian Nuclear Laboratories (CNL) looks to establish partnerships with vendors of SMR technology to develop, promote and demonstrate the technology in Canada, and continues annual calls for proposals of its Canadian Nuclear Research Initiative program (CNRI), with the fourth call for proposals announced in October 2024 [CNL, 2024]. CNL has agreements with SMR technology vendors, including GFP, StarCore Nuclear [CNL, 2019], Moltex Energy [CNL, 2020a], USNC [CNL, 2020b], NB Power [CNL, 2020c], Terrestrial Energy [CNL, 2020d], and ARC Canada [CNL, 2022].

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_2 encased in SiC pellets (USNC), coated UO_2 or UCO embedded in graphite pebbles (X-energy), or UO_2 (BWRX-300, SMR-160, NuScale). For comparison, current CANDU fuel is UO_2.

Internationally, there have been developments on the implementation of advanced reactors. FR projects are listed in Table 1. A summary of the global status of SMR projects can be found in NEA's SMR Dashboard [OECD/NEA, 2024]. The NEA notes that advanced reactors have the potential to reduce the quantity of high-level waste to be managed by deep geological repositories and the uranium resource requirements for the front end of the nuclear fuel cycle. At the time of publication of the 2024 edition, there was insufficient available information from verifiable public sources to assess the progress of SMRs in terms of waste management planning and readiness for end-of-life cycle management. Work on future editions of the NEA SMR Dashboard is expected to include the development of a methodology and criteria for assessing progress in this area.

In 2024, particularly in the United States, an increased interest was noted in using advanced reactors to provide electrical power for novel purposes such as Artificial Intelligence (AI) data centres. Google has entered a partnership with Kairos Power to support the development of multiple SMRs across the United States, with the first SMR online by 2030, followed with additional developments through 2035, aiming to provide 500 MW [Terrell, 2024]. Amazon and Energy Northwest have also made an agreement to advance development of four Xe-100 reactors [Energy Northwest, 2024]. Both SMR concepts are thermal reactors and involve open fuel cycles, but with higher enriched High-Assay Low-Enriched Uranium (HALEU) fuel. Additionally, in December 2024, Meta announced it will be releasing a request for proposals to identify nuclear energy developers to help meet AI innovation and sustainability objectives, targeting 1-4 GW of new nuclear capacity in the United States [Meta, 2024].

In the United States, a commercial FR project started non-nuclear construction in June 2024, with the potential for implementation of a limited closed fuel cycle. TerraPower's Natrium demonstration reactor project in Wyoming features a 345 MW sodium-cooled FR with HALEU molten salt fuel. TerraPower has submitted a construction permit application to the United States Nuclear Regulatory Commission [TerraPower, 2024].

Discussion on reprocessing

Advanced fuel cycles that are closed or partially closed require some type of reprocessing. The current commercial reprocessing technology as used in the facilities listed in Table 3 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.

A byproduct of the dissolved fuel is an aqueous high-level waste stream containing the majority of the fission products that must be managed. The preferred method of high-level waste treatment is through immobilization in glass at temperatures around 1,000°C, i.e. vitrification. The conditions found in the vitrification process are favourable to the release of volatile and semi-volatile radionuclides (such as I-129 and Cl-36) into an off-gas stream, which need to be captured and converted into a further appropriate waste form for geological disposal or released into the environment [OECD/NEA, 2022b].

Descriptions of the process used can be found in the technical literature such as [OECD/NEA, 2012].

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 high-level waste that must be stabilized for storage, then ultimately placed in a repository [OECD/NEA, 2020a, 2022b]. Additionally, significant quantities of process and operational low- and intermediate-level wastes (residues, structural materials, equipment, etc.) are generated through the process and require management in accordance with applicable industry standards and regulations.

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 – hydro-metallurgical 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 directly suitable for metallic and salt fuel, but can also be suitable for oxide fuels following pre-treatment such as by electrochemical reduction into metal [OECD/NEA, 2022b]. This approach has been employed in prototype FRs in the past (notably the United States Experimental Breeder Reactor program of the 1950s-80s [IAEA, 2012]) and has been proposed for other systems such as 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, 2012].) Argonne National Laboratory in the United States has developed a conceptual design for a pilot-scale pyroprocessing facility [Chang et al., 2018], and Korea had been conducting studies for demonstration at laboratory and engineering scale [OECD/NEA, 2019c].

Moltex Energy proposes to use a high temperature, molten salt-based form of pyroprocessing, called WATSS (WAste To Stable Salts) [Moltex, 2024], to convert spent oxide fuel (such as CANDU used fuel) to a salt form suitable for its Stable Salt Reactor – Wasteburner (SSR-W). A particular feature of its SSR-W 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. Moltex has reported completion of experiments to demonstrate the WATSS process using inactive simulated fuel and initiated experiments at CNL using CANDU used fuel in secure hot cells [Moltex, 2023]. In parallel, Moltex is engaged in discussions with the CNSC to formalize a service agreement to help facilitate a bilateral dialogue on its spent fuel recycling design [Moltex, 2023].

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, 2013] 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 U.S. DOE'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. 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 radioactive wastes that would require emplacement in a deep geological repository.

In general, studies show that the economics of open versus closed nuclear fuel cycles is dominated by the capital costs of reactors. Back-end fuel cycle costs typically have been estimated as less than 5 and up to 20 per cent of total nuclear power lifecycle cost. The consequence of this is that the choice of open or closed fuel cycle does not significantly affect the total economics, although it has consistently been shown that closed fuel cycles are on average higher cost than open fuel cycles, typically also in the range of less than 5 to 20 per cent. This is further emphasized that in the near term, closed fuel cycles require significantly longer time periods for economic benefits to be realized compared to open fuel cycles [Taylor et al., 2022].

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, 2023].

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. The availability of continuous high-power neutron beams is currently a key limiting factor, although experimental facilities have been designed and constructed in the world, producing results to inform conceptual designs for pilot ADS technology [IAEA, 2015].

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] and the 16th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (16IEMPT) [OECD/NEA, 2023].

Deep borehole disposal

A proposed alternative waste management approach is placing the used fuel in 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 vertically or horizontally 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 deep boreholes could have a number of technical advantages compared to mined geologic repositories for certain high-level waste types. These include a greater isolation of the waste and reduced mobility of radionuclides by increasing the depth, and improved modularity to expand the disposal capacity by drilling additional boreholes once a suitable area has been identified and licensed.

The deep borehole concept has been studied as an alternative to mined deep geological repositories in the United States [Sandia, 2009-2019; U.S. NWTRB, 2016; Deep Isolation, 2020; EPRI, 2020], Sweden [SKB, 1989-2013c; KASAM, 2007], the United Kingdom [NIREX, 2004], and elsewhere [von Hippel and Hayes, 2010; Chapman, 2013].

The concept of 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]. In 2023, the IAEA in response to interest from countries with small inventories (such as Australia, Croatia, Denmark, Norway and Slovenia) announced a new Coordinated Research Project to increase international knowledge and drive progress towards testing deep borehole disposal for intermediate-and high-level waste. The intention is to expand the scientific and technical groundwork demonstrating the safety and implementation of the deep borehole concept to provide the basis for potential future implementation [IAEA, 2023b].

The U.S. DOE began studies in 2009 on the deep borehole concept for disposal of spent fuel assemblies from U.S. reactors. Initial studies published by Sandia National Laboratories presented a preliminary evaluation of the concept [Sandia, 2009] and a reference design [Sandia, 2011a, 2011b]. 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, 2014; U.S. NWTRB, 2016]. The Deep Borehole Field Test Program involved the construction of at least one full-sized, non-radioactive deep borehole to a depth of 5 kilometres [Sandia, 2012c, 2015a, 2015b]. 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 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 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. They performed a public demonstration test in 2019, placing and retrieving a prototype canister from an existing deep horizontal borehole at about 600 metres underground [Deep Isolation, 2019].

Deep Isolation has performed post-closure safety analysis for disposal of light water reactor used fuel in about 1-kilometre-deep sub-horizontal boreholes in a hypothetical shale host rock, in waste containers assumed to fail after 10,000 years [Finsterle et al., 2020]. The results show that dose to the public can be low and acceptable in a suitable site. One uncertainty in performance is the potential for the boreholes themselves to act as a direct fast-flow pathway for radionuclides from failed disposal containers to the surface. Deep Isolation has performed numerical analysis into the effects of different sealing materials on radionuclide transport. The analysis shows that the large length-to-diameter ratio of the boreholes provides a significantly more important passive safety feature than the sealing material performance [Finsterle et al., 2021]. Another uncertainty in application to a real site is the effects of gas generation onto the host rock through corrosion of containers and waste [Finsterle et al., 2020].

Deep Isolation published a study commissioned by the United Kingdom Nuclear Decommissioning Authority subsidiary Nuclear Waste Services (NWS) to assess the role directional borehole technology might play in supporting the United Kingdom Government's strategic commitment to deep geological disposal of nuclear waste [Deep Isolation, 2023]. NWS concluded that directional borehole disposal could not replace the need for development of a deep geological repository in the United Kingdom, since it is not suited to the full diversity of the United Kingdom's waste inventory. A deep geological repository will be required, but directional borehole disposal could be considered in the future to dispose of some of the United Kingdom's high-level waste (e.g., high-level waste glass, used fuel and nuclear materials if classified as waste). Further development of directional borehole technology is required to increase the maturity for potential application to the conceivable inventory, including consideration of operational and post-closure safety [Deep Isolation, 2023]. The United Kingdom is working collaboratively with Deep Isolation to develop corrosion-resistant canisters for the United Kingdom's high-level waste (including used fuel) compatible with the directional disposal concept [Nuclear AMRC, 2023]. The first prototype canister was produced in early 2024 by the University of Sheffield Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC). The canister is planned to undergo field testing at the Deep Borehole Demonstration Center. In parallel, the University of Sheffield will validate the safety performance of the canister design through performance modelling in generic United Kingdom geologic environments. A second prototype canister is planned for manufacture in 2025 [Deep Isolation, 2024a]. Deep Isolation funded by a U.S. DOE research grant is also developing a Universal Canister System (UCS) for potential use as disposal containers for advanced reactor fuel waste in a deep geological repository or deep borehole disposal concepts. Prototype UCS containers have been fabricated and are planned to be used in field testing [Deep Isolation, 2024b].

While the concept of deep disposal for used fuel is considered to be technically feasible, there are questions on the approach, notably:

- Drilling of boreholes of the required diameter to the required depth has not yet been demonstrated;
- 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.

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, 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 relatively 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.
- There also continues to be international interest in deep borehole concepts. In Canada, the deep geological repository disposal concept and regulations have been developed over decades and discussed with potential host communities, and in 2024, a host site was selected based upon the deep geological repository concept. At this stage in the project, there does not appear to be any major benefits to shift disposal concept from mined deep geological repository to deep borehole disposal (horizontal or vertical).
- 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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