

# Watching Brief on Advanced Fuel Cycles

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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 coast-to-coast during 2002 to 2005. In considering different methods of managing used nuclear fuel, Canadians clearly and overwhelmingly identified the values and priorities for the long-term management of used nuclear fuel 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 be adaptable with flexibility for future generations to make their own decisions.

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

During the national study, Canadians expressed interest in knowing more about the possibility of recycling or reusing used CANDU nuclear fuel. The NWMO's analysis at that time concluded that reprocessing of used fuel appeared to be a highly unlikely scenario for Canada at that time. However, the NWMO recommended keeping a watching brief on the potential for change in the fuel cycle in Canada, and international technical research and advances.

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

- » Advanced fuel cycles are not likely to be implemented in Canada on a large scale in the near future.
- » Waste arising from alternative fuel cycles would be managed by the NWMO in a manner that is safe, socially acceptable, technically sound, environmentally responsible and economically feasible.
- » The NWMO will maintain a watching brief on alternative fuel cycle developments that could have an impact on Canada's future waste management requirements.

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

## Executive Summary

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, converted to mixed Pu-U oxide (MOX) fuel and reused once in current reactor types; and
- » “closed” or full recycle, in which the used fuel is reprocessed to recover plutonium and other actinides, then used to start up advanced fast neutron reactors (FRs). The FR used fuel is then reprocessed and continuously recycled in the FRs to extract additional energy. Depending on the configuration of the reactor, additional amounts of natural or depleted uranium or reprocessed used fuel can be added to replenish the fuel consumed in the FR. Other advanced reactor designs, such as molten salt reactors can also be used in closed fuel cycles.

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

As shown in Table 1, Canada, as well as most other nuclear power generating countries, currently follows the open fuel cycle. A few countries, such as Belgium, Germany, France, Japan, Netherlands, and Switzerland, use or have used partial recycling, with the used MOX fuel either stored as waste, or awaiting future recycling into possible future FRs. Recycled uranium from light water reactors (LWRs) is sometimes used as new fuel for CANDU type reactors in countries which operate both LWRs and heavy water reactors (HWRs), such as in China. Once it has been reused in the CANDU reactor, the used “natural uranium equivalent” (NUE) fuel is considered to be waste.

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

Work continued in 2014 in various countries and international collaborative programs to review and assess the technology and implications of advanced fuel cycles, including fully closed cycles based on reprocessing, partitioning and transmutation (RP&T). Findings were presented at several international conferences, including the annual World Nuclear Fuel Cycle conference (April 2014, San Francisco, California, United States); the International Congress on Advances in Nuclear Power Plants, ICAPP 2014 (April 2014, Charlotte, North Carolina, United States); the 22<sup>nd</sup> International Conference on Nuclear Engineering, ICONE-22 (July 2014, Prague, Czech Republic); the 13<sup>th</sup> Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (IEMPT-13) co-sponsored by the International Atomic Energy Agency (IAEA), the European Union and the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) (September 2014, Seoul, South Korea); and the

American Nuclear Society Topical Meeting on Reactor Physics, PHYSOR 2014 (October 2014, Kyoto, Japan).

Papers presented at these conferences showed that some advances are being made in the science and technology underlying RP&T and advanced fuel cycles, as well as in devising schemes to transition from current fuel cycles to the advanced ones. However, all these programs currently focus on recycling enriched uranium fuels, mostly LWR fuels, into next generation FR systems, and subsequent further continuous recycling of the advanced reactor fuels. Additional research and development would be required to assess their applicability to used CANDU fuels.

While some of the advanced fuel cycles are theoretically sustainable once they reach equilibrium, there are still many scientific and engineering challenges (such as development of suitable materials of construction for the very harsh conditions present in the advanced reactors and the scale up of lab-sized processes to full-sized), as well as socio-political and economic challenges, which must be solved before they can be implemented on an industrial scale. Indeed, a recent report co-authored by the European Commission's Joint Research Centre and the European Academies' Science Advisory Council states that "*Furthermore, the development of fast neutron reactor technology has been more difficult than expected*" [EASAC, 2014].

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

Cost is also an important consideration. In order to be successfully deployed on a commercial basis, the lifecycle cost of producing electricity with any advanced reactor or fuel cycle must be lower than for other production methods, including current nuclear power plants and non-nuclear technologies. A major study published in 2013 by the NEA of the OECD [OECD/NEA, 2013a] looked at lifecycle costs for various fuel cycle options and concluded that the once through fuel cycle was the least expensive at this time. The lifecycle costs include development, construction, operation, maintenance, decommissioning, and waste management related costs both for the power plant and for the associated fuel cycle facilities and transportation systems. All the proposed advanced fuel cycle schemes are based on the assumption of ongoing or expanding nuclear power programs for many decades or even centuries, as discussed in other studies on implementing the advanced fuel cycles [OECD/NEA, 2012b, 2013b; EASAC, 2014].

Beyond the primary benefit of energy security with these systems, a secondary benefit of the advanced fuel cycles is that it may reduce the demand for space in a high-level waste repository. However, this benefit can only be realized if alternative methods of managing the large volumes of long-lived intermediate-level waste resulting from reprocessing can be found and if some of the separated fission product wastes are stored for several hundred years prior to placement in a repository to allow the decay heat to dissipate. Otherwise, there is no significant benefit to the size or safety of a deep geological repository for high-level waste and used fuel. Indeed, a recent comprehensive review of used fuel management options for Korea conducted by the James Martin Center for Nonproliferation Studies of the Monterey Institute of International Studies states: "...no technical justification exists for P&T to be considered an alternative to direct geological disposal, and indeed, no evidence that any of the conventional P&T schemes could, even if they could be implemented, remove the need for deep geological disposal or even make disposal significantly easier or safer" [MII, 2013].

Similar to previous NWMO watching briefs on RP&T, the basic observations of this review remain unchanged:

- » Some form of deep geological repository is required regardless of the fuel cycle in order to be able to deal with long-lived radioactive wastes.
- » The waste management benefits of advanced fuel cycles are uncertain. Although RP&T has the potential to reduce the volume of used nuclear fuel and high-level waste for placement in a deep geological repository (when combined with advanced fuel cycles using FRs), it also significantly increases the quantity of long-lived low- and intermediate-level waste (which also requires a deep repository for long-term management) and does not significantly reduce the underground footprint of the repository. (For high-level waste and used fuel, repository size is based primarily on heat generation rate, not on volume of the waste. This is a function of the amount of energy extracted from the fuel, so it remains relatively constant per unit energy produced, regardless of fuel cycle.)
- » Advanced fuel cycles are at least many decades away from being ready for wide-scale commercialization due to the time required for the technical research, and to develop and demonstrate the reactor technologies. High cost and broad public acceptance issues that may accompany the “first-of-a-kind” designs may also inhibit their demonstration and deployment in the near term. Once a decision has been taken to deploy such fuel cycles, they will take many decades further to fully transition from current fuel cycles to the new ones, and decades to centuries to realize any waste management benefit from their implementation [OECD/NEA, 2013b].
- » Based on the current cost of uranium, the lifecycle cost of advanced fuel cycles is higher than once through fuel cycles, due to the high costs of developing and constructing the new generation reactors, reprocessing facilities and fuel fabrication plants. If such fuel cycles could be developed, the cost and project risks for implementing them on a commercial scale would currently make them very unattractive and financially risky for utilities to deploy.
- » Some countries currently engaged in fuel reprocessing, such as the United Kingdom, are considering discontinuing this practice due to the lower cost option of direct placement of used fuel in a deep geological repository. Other countries that have been developing commercial scale fuel reprocessing capability, such as Japan, are reconsidering their future fuel cycle options.
- » A few countries, such as Taiwan and Korea, are contemplating reprocessing existing used fuel as a means to extend the storage capacity at their reactor sites. The wet storage bays are near capacity, and they do not have the option to expand used fuel storage, either wet or dry. Therefore, their only option in the short term to allow the reactor fleet to remain in operation is having the used fuel reprocessed and storing the resulting high-level waste in order to free up space for additional used fuel. (Most other countries do not have this issue because they have the much less expensive option of dry storage of older used fuel and have sufficient capacity to expand the storage as needed.)

**Table 1: Summary of Current Status of Reprocessing for the Nuclear Power Fuel Cycle**

Country	Commercial Scale Reprocessing Facility		Currently Send Used Fuel for Reprocessing in Other Country	Decided to Cease Having Used Fuel Reprocessed	Planning Direct Placement of Used Fuel in a Repository
	Existing	Planned			
Belgium				✓	✓
Canada					✓
China <sup>(3)</sup>		✓			✓ <sup>(4)</sup>
Czech Republic				✓ <sup>(7)</sup>	✓
Finland				✓ <sup>(7)</sup>	✓
France <sup>(3)</sup>	✓ <sup>(2)</sup>				
Germany				✓	✓
Hungary				✓ <sup>(7)</sup>	✓
India <sup>(3)</sup>	✓				
Japan		✓ <sup>(6)</sup>	✓		
Korea, Rep. of					✓
Mexico					✓
Netherlands			Contract expires in 2015 <sup>(5)</sup>	✓	✓
Pakistan <sup>(3)</sup>					
Romania					✓
Russia <sup>(3)</sup>	✓				
Slovakia				✓ <sup>(7)</sup>	✓
Slovenia					✓
Spain					✓
Sweden				✓	✓
Switzerland				✓	✓
Ukraine				✓ <sup>(7)</sup>	✓
United Kingdom <sup>(3)</sup>	✓ <sup>(1)</sup>			✓	✓
United States <sup>(3)</sup>				✓	✓

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

(2) EDF recently planned to cease reprocessing its used fuel, but was required to continue for national policy reasons.

(3) China, France, the United Kingdom, Russia, the United States, Pakistan, and India currently reprocess for military reasons.

(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 extensions are being considered.

(6) Commercial-scale facility at Rokkasho-mura has been constructed and is undergoing test operation (currently planned to start commercial operation in 2016), but policy currently under review. Decision was taken to shut down pilot-scale facility at Tokai in 2014 because it was uneconomic to continue its operation.

(7) Some used fuel was sent to former Soviet Union for reprocessing. Practice terminated at end of USSR era.

These observations are consistent with those stated in previous NWMO watching brief reports [Jackson, 2008, 2009, 2010; NWMO, 2011, 2012a, 2013].

## Discussion

The NWMO has kept a watching brief on RP&T developments over the past few years. Previous detailed technical reports [Jackson, 2008, 2009, 2010] and summary watching brief reports [NWMO, 2011, 2012a, 2013] are available on the NWMO website. This present report focuses on the current status and a summary of recent international activities since the 2013 watching brief was published.

As reported in previous watching briefs, the U.S. Blue Ribbon Commission on America's Nuclear Future (BRC) conducted an extensive review in 2010 and 2011 of available options and technologies for management of the back end of the nuclear fuel cycle in the United States. In its final report [U.S. BRC, 2012a], the BRC stated (among other things):

- » *The conclusion that disposal is needed and that deep geologic disposal is the scientifically preferred approach has been reached by every expert panel that has looked at the issue and by every other country that is pursuing a nuclear waste management program.*
- » *...no currently available or reasonably foreseeable reactor and fuel cycle technology developments – including advances in reprocessing and recycling technologies – have the potential to fundamentally alter the waste management challenge this nation confronts over at least the next several decades, if not longer.*
- » *In any event, we believe permanent disposal will very likely also be needed to safely manage at least some portion of the commercial spent fuel inventory even if a closed fuel cycle were adopted.*

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

Research on RP&T and advanced fuel cycles is ongoing in the United States and other parts of the world. Findings were presented at several recent international conferences, including the annual World Nuclear Fuel Cycle conference (April 2014, San Francisco, California, United States) [WNA, 2014]; the International Congress on Advances in Nuclear Power Plants, ICAPP 2014 (April 2014, Charlotte, North Carolina, United States) [ICAPP, 2014]; the 22<sup>nd</sup> International Conference on Nuclear Engineering, ICONE-22 (July 2014, Prague, Czech Republic) [ICONE, 2014]; the 13<sup>th</sup> Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation co-sponsored by the IAEA, the European Union and the OECD NEA (September 2014, Seoul, South Korea) [OECD/NEA, 2014]; and the American Nuclear Society Topical Meeting on Reactor Physics, PHYSOR 2014 (October 2014, Kyoto, Japan) [PHYSOR, 2014], as well as at past conferences, including the IAEA Fast Reactor conference (March 2013, Paris, France) [IAEA, 2013a]; the International Conference on Emerging Nuclear Energy Systems (May 2013, Madrid, Spain) [ICENES, 2013]; the OECD/NEA 2<sup>nd</sup> International Workshop on Technology and Components of Accelerator Driven Systems (May 2013, Nantes, France) [OECD/NEA, 2013c]; and GLOBAL 2013 (September 2013, Salt Lake City, United States) [GLOBAL, 2013]. Papers presented at these conferences, as well as technical reports published by the OECD/NEA [e.g., OECD/NEA, 2011, 2012b, 2012c, 2013a, 2013b], IAEA [e.g., IAEA, 2012, 2013b, 2013c], U.S. Nuclear Regulatory Commission [U.S. NRC, 2012], and various international collaborative projects (such as the European Sustainable Nuclear Energy Technology Platform [SNETP, 2013], and Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution [ASGARD, 2013] projects), showed that advances are being made in the science and technology underlying RP&T and advanced fuel cycles. Some of the potential advanced fuel cycle concepts and options are discussed below.

All the commercial nuclear power reactors in operation around the world today are based on thermal neutrons. In this type of reactor, a moderator is used to slow down (or thermalize) the high energy neutrons produced by the fission reaction so that they can induce further fission in the U-235 and/or Pu-239 isotopes in the nuclear fuel. Moderating materials include normal or light water (used in most non-CANDU reactors around the world), heavy water (used in CANDU reactors) and graphite (mainly used in gas cooled reactors). The moderating materials have different properties for interacting with the neutrons. For example, heavy water moderated reactors can sustain a nuclear chain reaction in natural (un-enriched) uranium, which contains about 0.7% of U-235 with the rest being U-238. On the other hand, light water (used in many other places in the world in boiling water reactors (BWRs) and pressurized water reactors (PWRs), collectively known as LWRs) requires a higher concentration of U-235 (generally 3% to 5%) to work. Producing this higher concentration is known as enrichment. Operation of current reactor types requires a continuous supply of fresh uranium as a source of the fissile U-235. A byproduct of this process is depleted uranium, which has a reduced U-235 content of around 0.3% and is now generally considered to be a waste by countries that operate enrichment facilities. However as noted below, the depleted uranium from the enrichment process is a potential fuel source for some advanced reactor fuel cycles.

There are two main technical reasons why a RP&T program or advanced fuel cycle could be implemented:

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

The first reason is based on the premise that uranium is too scarce or costly to use in a once through fuel cycle and should be preserved, or that indigenous supplies are limited and that access to foreign supplies is unreliable. The second reason is based on the premise that used fuel from existing reactors can be recycled into FRs, that there will be an ongoing nuclear power program for many decades (or even centuries) and that suitable repository space to manage the resulting wastes will be scarce. Both reasons also assume that other energy alternatives are more costly and nuclear energy is the most economic choice for a given country. Note also that although recycling of used fuel into FRs may reduce the volume of high-level waste produced per megawatt of electricity generated, it does not always significantly reduce the required footprint area of a repository. This is because the footprint is governed by the thermal output of the waste, not by its volume. Wastes from advanced nuclear fuel cycles tend to be hotter, thus requiring more repository space per unit volume. Only in the case of very advanced fuel cycles, with full partitioning and transmutation of all actinides maintained over long periods of time, is there any significant reduction in high-level waste repository space requirements. Even in these extreme cases, the reduction in high-level waste repository space is somewhat offset by the large increase in the long-lived intermediate-level wastes resulting from these fuel cycles (which also requires long-term management in a deep repository).

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



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

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

Current advanced reactor concepts operate at very high temperatures (typically 400°C or more) and use liquid metals (e.g., sodium or lead), molten salts (e.g., sodium fluoride mixtures) or gases (e.g., helium) as coolants rather than water or heavy water. There are a number of prototypes and/or designs that are being promoted by various countries as part of the international GEN-IV collaborative project and by several commercial enterprises. The details of these designs are described elsewhere, such as [GIF, 2014].

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

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

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

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

Some reactor concepts, such as many of the molten salt designs, require a makeup supply of fresh slightly enriched to highly enriched fuel to operate, which make them unsuitable to work with used CANDU fuel directly (although they may be suitable for used LWR fuel) [Transatomic Power, 2014]. In this instance, used CANDU fuel would require blending with enriched uranium in order to create the correct fuel mixture of at least about 2% enrichment.



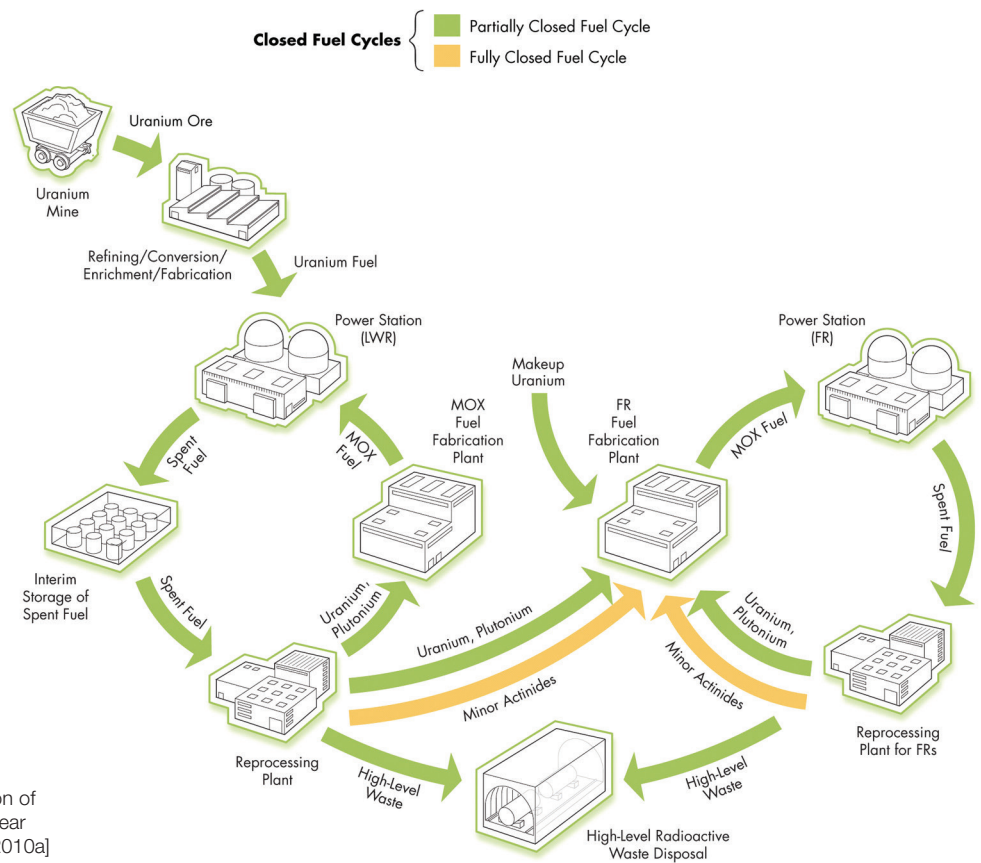


Figure 1: Illustration of an advanced nuclear fuel cycle [EPRI, 2010a]

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

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

In addition to being a significant cost, the rate at which the plutonium can be supplied limits the speed at which the FRs can be deployed. Most scenarios studied (e.g., in France and Japan) require 50 to 100 years or more to transition from thermal reactors to FRs in a step-wise fashion, and a further several hundred years or more to effectively consume the used fuel from current LWRs, assuming a large fleet of FRs. (See, for example, [MIT, 2011], [OECD/NEA, 2009, 2012b, 2013b], Warin and Boullis in [OECD/NEA, 2012a], and [EASAC, 2014].) This long transition time imposes a commitment on future generations to operate and maintain an advanced nuclear power program (including periodic replacement of the nuclear fleet and associated fuel cycle facilities), but it also gives them access to significant quantities of low-carbon energy, should they choose to exploit this source of energy.

Many of the studies point out that in addition to the used nuclear fuel, there is sufficient depleted uranium available (from LWR fuel enrichment) to sustain such a system globally for many centuries, if not millennia, since each reactor would typically consume only a few hundred kilograms of uranium or other heavy actinides per year as makeup fuel. In fact, the use of existing depleted uranium is often the preferred fuel, since it is widely available and relatively clean both radiologically (low dose rate) and isotopically (free of fission products and other contaminants). More than 1 million tonnes of depleted uranium are currently stockpiled around the world.

To put the FR fuel usage in perspective, if each FR consumed 500 kilograms of fuel per year, the current (as of June 2014) ~50,000-tonne inventory of used fuel in Canada [NWMO, 2014] could provide electricity for some 100,000 reactor years of operation (e.g., a fleet of 100 reactors operating for 1,000 years). Since the reactors are currently designed for a life of about 60 years, 16 generations of reactors would be required to give the required lifespan of 1,000 years, for a total of 1,600 reactors built, operated and decommissioned. In theory, the required time span to consume most of the problematic transuranic elements (i.e., plutonium and minor actinides) in the used fuel could be reduced to within a hundred years if they were to be completely separated from the U-238 in the used fuel, and there was no delay in FR 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.

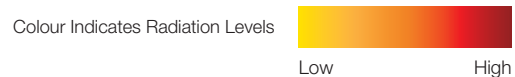
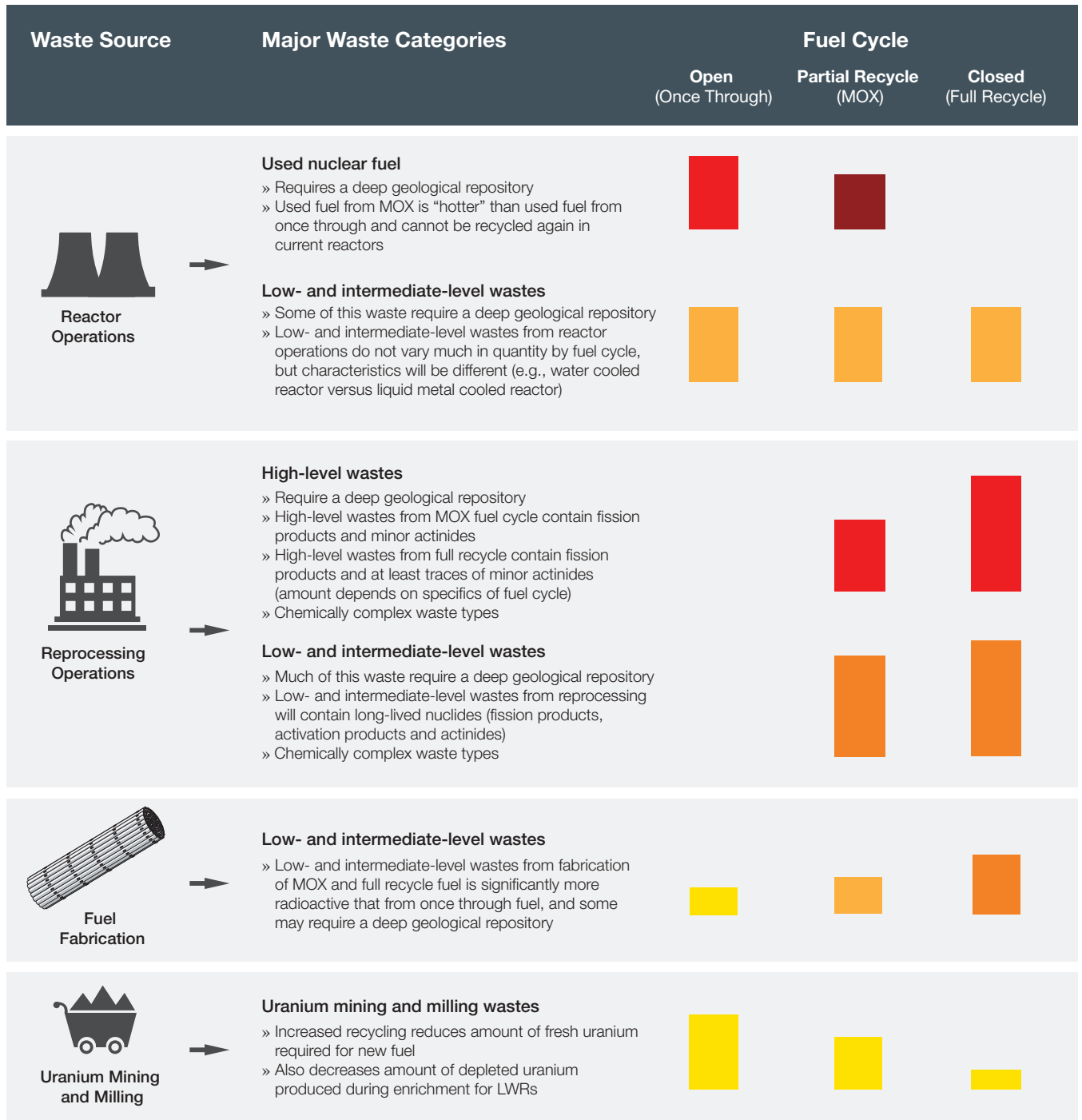


Figure 2: Illustration of wastes produced by different fuel cycles

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

Most FR scenarios rely on different fuel types than those that are currently used, such as metallic fuels, molten salts or silicon carbide/graphite coated fuel particles. These fuel types are not compatible with the current wet chemical processing technology used for LWR uranium-oxide-based fuels. A non-aqueous technology (“pyro-processing”) is being developed for these fuels. However, although this has been employed in prototype FRs in the past (e.g., the U.S. Experimental Breeder Reactor (EBR) program of the 1950s to 1980s [IAEA, 2012]) and has been proposed for other systems, such as IFR and PRISM [Triplet et al., 2012], pyro-processing has not yet achieved commercial-scale implementation. (See, for example, Iizuka et al. in [OECD/NEA 2012a].) In addition, many FRs require complex reprocessing facilities to remove the buildup of undesirable actinides and fission products in the fuel resulting from multiple recycling. Remote handling is also required for recycled fuel fabrication due to the presence of nuclides which emit high-energy gammas.

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

Other proposals include the introduction of small modular reactors (SMRs). SMRs are up to a few tens of megawatts in size and are being proposed for use in remote (i.e., off-grid) communities and resource extraction sites which currently rely on small-scale fossil fuel generating plants to provide heat and/or electricity. The reactors are based on a variety of non-CANDU technologies, including liquid metal cooled, molten salt cooled and light water cooled designs.

There are currently no active environmental assessments or licence applications underway in Canada for any of these proposals. However, the NWMO will continue to monitor the situation and will evaluate the implications and options for any new reactors as part of APM.

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

resulted in the establishment of various international consortia (e.g., the Generation IV International Forum [GIF, 2014]) and commercial entities pursuing various designs and fuel cycle options.

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

## Observations and Conclusions

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

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

The main conclusions from the NWMO perspective are:

- » Advanced fuel cycles are not likely to be implemented in Canada on a large scale in the near future.
- » Waste arising from alternative fuel cycles would be managed by the NWMO in a manner that is safe, socially acceptable, technically sound, environmentally responsible and economically feasible.
- » The NWMO will maintain a watching brief on alternative fuel cycle developments that could have an impact on Canada's future waste management requirements.

## Key References

- ASGARD, 2013. Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution, a project within the European Union 7<sup>th</sup> Framework Programme.  
([www.asgardproject.eu](http://www.asgardproject.eu))
- EASAC, 2014. Management of Spent Nuclear Fuel and its Waste. EASAC policy report no. 23, prepared by the European Academies' Science Advisory Council, July 2014.  
([www.easac.eu](http://www.easac.eu))
- GIF, 2014. Generation IV International Forum.  
([www.gen-4.org](http://www.gen-4.org))
- GLOBAL, 2013. International Nuclear Fuel Cycle Conference, organized by the American Nuclear Society, September 29–October 3, 2013, Salt Lake City, Utah, United States.  
([www.ans.org/meetings/m\\_158](http://www.ans.org/meetings/m_158))
- IAEA, 2012. Status of Fast Reactor Research and Technology Development. Report # IAEA-TECDOC-1691, prepared by the International Atomic Energy Agency, December 2012.  
([www.iaea.org](http://www.iaea.org))
- IAEA, 2013a. FR13 – International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios, March 4–7, 2013, Paris, France.  
([www-pub.iaea.org/iaeameetings/41987/International-Conference-on-Fast-Reactors-and-Related-Fuel-Cycles-Safe-Technologies-and-Sustainable-Scenarios-FR13](http://www-pub.iaea.org/iaeameetings/41987/International-Conference-on-Fast-Reactors-and-Related-Fuel-Cycles-Safe-Technologies-and-Sustainable-Scenarios-FR13))
- IAEA, 2013b. Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability – Final Report of the INPRO Collaborative Project GAINS. Report # NP-T-1.14, prepared by the International Atomic Energy Agency, November 2013.  
([www.iaea.org](http://www.iaea.org))
- IAEA, 2013c. Design Features and Operating Experience of Experimental Fast Reactors. Report # NP-T-1.9, prepared by the International Atomic Energy Agency, November 2013.  
([www.iaea.org](http://www.iaea.org))
- ICAPP, 2014. 2014 International Congress on Advances in Nuclear Power Plants, organized by the American Nuclear Society, April 6–9, 2014, Charlotte, North Carolina, United States.  
([www.ans.org/meetings/m\\_198](http://www.ans.org/meetings/m_198))
- ICENES, 2013. 16<sup>th</sup> International Conference on Emerging Nuclear Energy Systems, organized by the Escuela Técnica Superior de Ingenieros Industriales, May 26–30, 2013, Madrid, Spain.  
([www.icenes2013.org](http://www.icenes2013.org))
- ICONE, 2014. 22<sup>nd</sup> International Conference on Nuclear Engineering, organized by the American Society of Mechanical Engineers, July 7–11, 2014, Prague, Czech Republic.  
([www.asmeconferences.org/ICONE22/index.cfm](http://www.asmeconferences.org/ICONE22/index.cfm))
- INL, 2012. Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating Costs. Report TEV-1196 prepared by Idaho National Laboratory, January 2012.  
([www.inl.gov](http://www.inl.gov))



Jackson, 2003. Status of Nuclear Fuel Reprocessing, Partitioning and Transmutation. NWMO Background Paper 6-4 prepared for the NWMO by David P. Jackson & Associates Ltd., November 2003.  
([www.nwmo.ca](http://www.nwmo.ca))

Jackson, 2005. Implications of Reprocessing, Partitioning and Transmutation on Long-Term Management of Used Nuclear Fuel in Canada. NWMO Background Paper 6-14 prepared for the NWMO by David P. Jackson & Associates Ltd., February 2005.  
([www.nwmo.ca](http://www.nwmo.ca))

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](http://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](http://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](http://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](http://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](http://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.  
([mitei.mit.edu/publications/reports-studies/future-nuclear-fuel-cycle](http://mitei.mit.edu/publications/reports-studies/future-nuclear-fuel-cycle))

NWMO, 2011. Watching Brief on Reprocessing, Partitioning and Transmutation – 2011.  
([www.nwmo.ca](http://www.nwmo.ca))

NWMO, 2012a. Watching Brief on Reprocessing, Partitioning and Transmutation – 2012 Update.  
([www.nwmo.ca](http://www.nwmo.ca))

NWMO, 2012b. Used Fuel Repository Conceptual Design and Postclosure Safety Assessment in Crystalline Rock. NWMO Report TR-2012-16, December 2012.  
([www.nwmo.ca](http://www.nwmo.ca))

NWMO, 2013. Watching Brief on Reprocessing, Partitioning and Transmutation – 2013 Update.  
([www.nwmo.ca](http://www.nwmo.ca))

NWMO, 2014. Nuclear Fuel Waste Projections in Canada – 2014 Update. NWMO Report TR-2014-16, December 2014.  
([www.nwmo.ca](http://www.nwmo.ca))

- OECD/NEA, 2009. Nuclear Fuel Cycle Transition Scenario Studies. Report # 6194, prepared by the OECD NEA, February 2009.  
([www.oecd-nea.org](http://www.oecd-nea.org))
- OECD/NEA, 2011. Trends Towards Sustainability in the Nuclear Fuel Cycle. Report # 6980, prepared by the OECD NEA, April 2011.  
([www.oecd-nea.org](http://www.oecd-nea.org))
- OECD/NEA, 2012a. 12<sup>th</sup> Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, organized by the OECD NEA, September 24–27, 2012, Prague, Czech Republic.  
([www.oecd-nea.org](http://www.oecd-nea.org))
- OECD/NEA, 2012b. Homogeneous Versus Heterogeneous Recycling of Transuranics in Fast Nuclear Reactors. Report # 7077, prepared by the OECD NEA, December 2012.  
([www.oecd-nea.org](http://www.oecd-nea.org))
- OECD/NEA, 2012c. Spent Nuclear Fuel Reprocessing Flowsheet. Report # NEA/NSC/WPFC/DOC(2012)15, prepared by the OECD NEA, June 2012.  
([www.oecd-nea.org](http://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](http://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](http://www.oecd-nea.org))
- OECD/NEA, 2013c. 2<sup>nd</sup> International Workshop on Technology and Components of Accelerator Driven Systems (TCADS-2), organized by the OECD NEA, May 21–23, 2013, Nantes, France.  
([www.oecd-nea.org](http://www.oecd-nea.org))
- OECD/NEA, 2014. 13<sup>th</sup> Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (IEMPT-13), organized by the OECD NEA, September 23–26, 2014, Seoul, South Korea.  
([www.oecd-nea.org](http://www.oecd-nea.org))
- PHYSOR, 2014. International Conference on The Role of Reactor Physics towards a Sustainable Future, organized by the American Nuclear Society and the Japan Atomic Energy Agency, September 28–October 3, 2014, Kyoto, Japan.  
(<http://rpg.jaea.go.jp/physor2014>)
- Sandia, 2012. Influence of Nuclear Fuel Cycles on Uncertainty of Geologic Disposal. Report # FCRD-UFD-2012-000088, prepared for the U.S. Department of Energy Used Fuel Disposition Campaign by Sandia National Laboratories, July 2012.  
([www.energy.gov](http://www.energy.gov))
- SNETP, 2013. The Sustainable Nuclear Energy Technology Platform, a program within the framework of the European Commission Strategic Energy Technology Plan.  
([www.snetp.eu](http://www.snetp.eu))
- Transatomic Power, 2014. Technical White Paper, v1.0.1, March 2014.  
([www.transatomicpower.com](http://www.transatomicpower.com))

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](http://www.gehitachiprism.com))**

U.S. BRC, 2012a. Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy, January 2012.

**(<http://energy.gov/ne/downloads/blue-ribbon-commission-americas-nuclear-future-report-secretary-energy>)**

U.S. BRC, 2012b. Reactor and Fuel Cycle Technology Subcommittee Report to the Full Commission – Updated Report, January 2012.

**(<http://energy.gov/ne/downloads/blue-ribbon-commission-americas-nuclear-future-report-secretary-energy>)**

U.S. BRC, 2012c. Transportation and Storage Subcommittee Report to the Full Commission – Updated Report, January 2012.

**(<http://energy.gov/ne/downloads/blue-ribbon-commission-americas-nuclear-future-report-secretary-energy>)**

U.S. BRC, 2012d. Disposal Subcommittee Report to the Full Commission – Updated Report, January 2012.

**(<http://energy.gov/ne/downloads/blue-ribbon-commission-americas-nuclear-future-report-secretary-energy>)**

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](http://www.nrc.gov))**

WNA, 2014. World Nuclear Fuel Cycle Conference, organized by the World Nuclear Association and the Nuclear Energy Institute, April 7–10, 2014, San Francisco, United States.

**([www.wnfc.info](http://www.wnfc.info))**



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