Considerations in Recycling Used Natural Uranium Fuel from CANDU Reactors in Canada

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Abstract

This paper identifies the key factors that would affect the recycling of used natural uranium (NU) fuel from CANDU® reactors which are in operation in Canada and in several other countries. There has been little analysis of those considerations over the past 25 years and this paper provides a framework for such analysis. In particular, the large energy potential of the plutonium in used CANDU NU fuel provides a driver for consideration of used-fuel recycling. There would be a long lead-time (at least 30 years) and a large investment required for establishing the infrastructure for used-fuel recycling. While this paper does not promote the recycling of used CANDU NU fuel in Canadian CANDU reactors, it does suggest that it is timely to start the analysis and to consider the key factors or circumstances that warrant the recycling of used CANDU NU fuel.

1. Introduction

From the earliest days of nuclear power, the recycling of fissile material in used fuel from conventional thermal reactors was seen as eventually being necessary to ensure long-term availability of fuel resources. Decisions to invest in commercial, civilian reprocessing technology were largely taken with a view towards using plutonium from used Light Water Reactor (LWR) fuel in future fast breeder reactors, to ensure a long-term supply of nuclear fuel material. However, early predictions of uranium shortages have not materialized and used LWR fuel has been either stored or the plutonium recycled as mixed-oxide (MOX) fuel in LWRs. Uranium from reprocessed LWR fuel (RU) has been re-enriched and recycled as new fuel in some European LWRs. In China a demonstration irradiation began on March 22, 2010 on the simplest of all recycling opportunities – the blending of RU with depleted uranium (DU) from enrichment plant tails as "natural uranium equivalent" fuel – in the Qinshan Unit 1 CANDU reactor [1].

W.B. Lewis identified the "value-breeder" fuel cycle with thorium fuel and the recycling of U-233 to provide long-term resource security for Canada using the CANDU reactor [2]. Much early R&D was done in AECL on recycling technology, applied to both uranium and thorium fuels. Reactor physics tests continue to this day at AECL's Chalk River Laboratories, as well as fabrication, irradiation and post-irradiation examination (PIE) of test fuels relevant to the recycling of fissile material from used nuclear fuel within CANDU reactors.

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Over the past 25 years, market forces have provided little incentive to look at the recycling of used CANDU NU fuel for resource extension: CANDU reactor fuelling costs are the lowest of any other commercial reactor by a factor of two (on the basis of electricity produced, i.e., $\$/kWh_e$); uranium has been relatively inexpensive; and the concentration of fissile material in used CANDU NU fuel is low (nominally 0.2% U-235 and 0.27% fissile plutonium) as compared to that in used LWR fuel (nominally 0.9% U-235 and 0.6% fissile plutonium). In AECL, the focus of studies has been on the recycling of used LWR fuel within CANDU reactors since used LWR fuel has a higher fissile content while high neutron economy makes the CANDU reactor the most effective reactor available to extract that energy potential [3]. Due to growing energy demand in developing countries, concerns over climate change effects, plus actual and potential increases in gas and oil prices, recent predictions are of a sharp increase in uranium demand. This has re-ignited concerns over uranium availability and its price beyond 2040 [4]. Canada, with its large uranium reserves, will be subject to the same international pressures on uranium supply and price, so resource extension is one potential driver for recycling the plutonium in used CANDU NU fuel.

A second potential driver for considering the recycling of used CANDU NU fuel is the environmental impact of the fuel cycle. Internationally, there is research into the possibility of partitioning the used fuel into its constituents and transmuting (fissioning) the long-lived actinides into shorter-lived fission products. The aim of this partitioning and transmutation (P&T) is to reduce the long-term radiotoxicity and decay heat from the emplacement of used fuel or derived recycling wastes in a Deep Geological Repository (DGR). AECL has responded to this interest by showing that the CANDU reactor would be a very effective complement to a system of LWRs and fast-spectrum reactors for consuming the actinides from used LWR fuel [5-7]. However, AECL has not looked at the possible environmental benefits of recycling used CANDU NU fuel, including the possible reduction of long-term radiotoxicity and decay heat, so there is the potential of an environmental driver for recycling used CANDU NU fuel. If used fuel were recycled, then there would also be the opportunity for extracting isotopes that could be of value for medical or industrial purposes.

In Canada, the Nuclear Waste Management Organization (NWMO) has the responsibility for implementing the Adaptive Phased Management (APM) approach for the long-term management of used nuclear fuel [8-12]. "*APM links a technical method with a management system that can embrace change in technology and science, societal values and public policy. Technically, APM has as its end-point the containment and isolation of used nuclear fuel in a deep repository constructed in a suitable rock formation*" [9]. APM envisages a period of long-term retrievable storage of used fuel before the DGR is sealed and it accommodates the possibility of new, advanced technologies for dealing with used nuclear fuel (such as recycling). The NWMO states that "*While used nuclear fuel will be retrievable throughout all phases of implementation of APM, it is expected that the process of retrieval will become progressively more demanding and resource intensive as the used fuel containers are sealed in the placement rooms and the access tunnels and shafts are eventually backfilled and sealed. The future decision to close the deep geological repository will only be made once the society and government institutions and processes of the day agree that this should happen"* [11]. The APM approach would be valid for used-fuel recycling, since a DGR would still be required to dispose of the residual high-level recycling wastes, and there would be time to

develop recycling technology. The NWMO maintains a watching-brief on used-fuel recycling technology world-wide [13].

It is now timely to re-examine the recycling of used CANDU NU fuel. This paper identifies at a high level the key factors that would need to be considered in the Canadian and international context.

- The energy potential of the plutonium in used CANDU NU fuel is examined in Section 2.
- Environmental and waste management considerations, both for direct emplacement of used CANDU NU fuel in a DGR and for recycling options, including P&T, are identified in Section 3.
- The processes for used-fuel recycling and the challenges of recycle-fuel manufacturing are identified in Section 4.
- The impact of using recycled fuel in CANDU reactors on reactor design and operation are discussed in Section 5.
- Used-fuel recycling would change the risk profile associated with the fuel cycle, adding a higher, near-term risk to the miniscule, long-term risk from used-fuel emplacement in a DGR, as discussed in Section 6.
- Safeguards and proliferation resistance must be considered up front in the design of the fuel cycle, and some aspects are mentioned in Section 7.
- A key determinant in the viability of used-fuel recycling will be the economics of the entire fuel cycle, from mining, through fuel manufacturing, through electricity production, to used-fuel management, as discussed in Section 8.
- Finally, technology serves people. Any initiative on used-fuel recycling would have to meet domestic and international regulatory requirements. There would also need to be public acceptance of the benefits of used nuclear fuel recycling – a waste-to-energy approach. This is discussed in Section 9.

Note that the following high-level analysis is largely qualitative since detailed studies have not begun.

2. Used CANDU NU fuel: a potential energy resource

The concentration of plutonium in used CANDU NU fuel is less than 40% of that in used LWR fuel: ~3.7 g Pu/kg HE (heavy element) [14] compared with ~10 g Pu/kg HE for used LWR fuel [15], depending on the burnup. In both cases, about 70% of the plutonium is fissile (Pu-239 + Pu-241), with a smaller fissile fraction in high-burnup used LWR fuel. It is noted that this plutonium is “reactor grade” as opposed to “weapons grade” (the latter typically comprising ~93% Pu-239). In used LWR fuel, a larger fraction is Pu-241 (about 14% compared to 6% in used CANDU fuel) and this decays with a 14.4 year half-life to Am-241, so used LWR fuel loses a greater fraction of its fissile content over time than does used CANDU NU fuel.

The uranium in used CANDU NU fuel contains ~0.2% U-235, so there is no economic incentive for its recovery since there are enormous quantities of DU available from enrichment-plant tails

(containing typically between 0.15 and 0.3% U-235). Used LWR fuel has about 0.9% residual U-235. So in total, used CANDU NU fuel has about one-fifth of the amount of recoverable fissionable material compared with used LWR fuel. This has obvious implications on the relative cost of recovering and recycling fissile material from used CANDU NU fuel compared with used LWR fuel. A country having both LWRs and CANDU reactors would surely recycle their used LWR fuel before considering recycling used CANDU NU fuel.

Since there is no economic incentive for the separate recovery of uranium, which comprises ~ 99% of the used CANDU NU fuel, it could be: co-extracted with the plutonium as Pu/DU MOX fuel (giving the desired concentration of plutonium in the MOX fuel); co-extracted with the fission product and minor actinide (neptunium, americium and curium) wastes as an immobilization matrix; or separated, purified and disposed of as long-lived, low- or intermediate-level waste. This will be further discussed in Section 3.2.

The current nuclear fleet in Canada (~15 GWe) [16] will result in between 56,000 and 110,000 Mg of used fuel over the lifetime of the reactors, depending upon future refurbishment decisions [17], which will contain between 200 and 400 Mg of plutonium. If one considers, for instance, 100,000 Mg of used CANDU NU fuel, containing ~370 Mg of reactor-grade plutonium, what is the energy potential of this material and how could it be best used as CANDU reactor fuel to extend the commercial uranium resources in Canada? These are the questions considered in the next section.

2.1 Fuel cycle options for recycling plutonium in a CANDU reactor

AECL's studies of fuel recycling have focused on recycling uranium and plutonium from used LWR fuel into CANDU reactors. The last significant assessment of the potential for recycling the plutonium from used CANDU NU fuel back into CANDU reactors was done by Veeder and Didsbury [14]. That study provides insights into the energy potential from a variety of CANDU advanced fuel cycle options, including the use of plutonium from used CANDU NU fuel as the fissile topping for uranium- or thorium-based MOX fuels with multiple recycling of the self-generated plutonium. That analysis is only indicative of the energy potential from the various plutonium-recycling options in a CANDU reactor as it is based on simple lattice calculations, with no account of reactor core constraints such as fuel management, reactor control and safety, the values of reactivity coefficients, or restrictions on the use of separated fissile material.

2.1.1 CANDU MOX fuel

By using the 370 Mg plutonium extracted from 100,000 Mg of used CANDU NU fuel as the initial fissile component of Pu/DU MOX fuel (as well as for topping up the recycled plutonium from multiple-recycling of the MOX fuel to maintain the desired burnup), the existing 15 GWe nuclear fleet in Canada could be fuelled for over 40 years at an assumed capacity factor of 85% without the need for additional NU (based on Veeder and Didsbury [14]). This is indeed a large amount of energy and on its own would justify a more detailed assessment of all of the factors to be considered in plutonium recycling. The analysis in [14] does not address single recycling, followed by emplacement of the used CANDU MOX fuel in a DGR.

Mixing enough plutonium (0.4% Pu) with NU to achieve a burnup of ~17 MWd/kg results in a Pu/NU MOX cycle that is self-sufficient in recycled plutonium (i.e., once the initial plutonium is provided no additional plutonium is required beyond that recycled in the used MOX fuel to achieve this burnup, although additional NU is required). In this cycle, the addition of a small amount of plutonium to the initial UO_2 more than doubles the NU fuel burnup. This cycle would provide twice the energy compared to NU on its own, and over four times the energy from the plutonium compared to Pu/DU MOX fuel. This is probably the most efficient (but not necessarily the most economical) uranium MOX cycle in terms of energy from the recycled plutonium. Of course, the plutonium could also be mixed with RU from reprocessed used LWR fuel for even greater benefit.

In both the Pu/DU and Pu/NU MOX multiple-recycle options, increasing the burnup reduces the efficiency of plutonium utilization (more plutonium is required per unit of energy produced), so high-burnup fuel technology is not needed to realize the full benefit from CANDU MOX fuel. However, fuel cycle economics, particularly the cost of used-fuel processing and recycle-fuel manufacturing will favour higher burnups.

2.1.2 CANDU Pu/Th fuel

Similar benefits are derived when using the plutonium to initiate the thorium cycle (Pu/Th). In this cycle, fissile U-233 is produced via neutron capture in Th-232 and the subsequent beta decay of Th-233 and Pa-233. For example, Veeder and Didsbury [14] considered multiple recycling of self-generated uranium, but only one recycle of the plutonium, with additional plutonium topping to give the required burnup. The large benefit with thorium comes in the replacement reactor that inherits the U-233 from the initial unit.

The full energy potential from plutonium recycling in the CANDU reactor could be realized through the Self-Sufficient Equilibrium Thorium (SSET) cycle, which could also be the ultimate vision for achieving nuclear resource self-sufficiency in Canada. In this cycle, the uranium (mainly U-233) produced in the thorium fuel would be recycled (possibly with the thorium). The analysis in [14] indicates that at equilibrium the SSET CANDU cycle, initiated with the 370 Mg plutonium from 100,000 Mg of used CANDU NU fuel with uranium recycling, could indefinitely sustain a nuclear capacity two to three times greater than the current nuclear capacity in Canada. Even greater neutron economy would be required to achieve the SSET cycle than in the current CANDU reactor. This could be achieved by further optimizing the fuel bundle and lattice designs; use of higher purity D_2O; use of “enriched zirconium” fuel channels in which the higher-absorbing Zr-91 isotope has been reduced; operation with a reduced adjuster-rod loading; and operation at lower flux levels to reduce parasitic absorption in Pa-233. Operation with a gas coolant would provide about 15 mk in reactivity and eliminate the positive coolant void reactivity of the current CANDU NU reactor (enhancing passive safety). These features would define an R&D path and an evolutionary reactor development path towards a resource-sustainable CANDU reactor future.

Hence, the plutonium from used CANDU NU fuel is an important energy resource that could contribute substantially to resource extension and sustainability in Canada. This, on its own,

does not justify used-fuel recycling in Canada, but does warrant consideration of the other important factors.

3. Environmental and waste-management considerations

The environmental and waste-management impact of recycling used CANDU NU fuel (once or multiple times) needs careful consideration over the entire fuel cycle, and should be compared with the once-through use of NU in a CANDU reactor followed by direct emplacement of the used fuel in a DGR. This section discusses the environmental aspects of managing the used fuel or recycle wastes at the back end of the cycle. Section 3.1 deals with emplacement of used CANDU NU fuel in a DGR: the design aspects of a DGR that isolates the radioactivity from humans and the biosphere; the contributors to dose exposure from a DGR; how the decay heat from the used fuel affects the DGR design; and the concept of radiotoxicity. Section 3.2 addresses the environmental impact of recycling used CANDU NU fuel from two perspectives: whether there is an environmental driver for considering recycling; and if used-fuel recycling is being pursued for other reasons such as for resource extension, what are some of the environmental considerations.

3.1 Once-through CANDU NU fuel cycle

The main direct environmental impacts from the fuel cycle with once-through CANDU NU fuel would arise from mine tailings in the front end and the direct emplacement of the used fuel in a DGR at the back end. There has been a significant amount of study of the direct emplacement of used nuclear fuel in a DGR in Canada and internationally [18-23]. In Finland, the government selected a site for a final disposal facility for spent nuclear fuel for which there is a willing host community and construction of an underground characterization facility is proceeding. In Sweden also, a site has been selected from a willing host community. In the U.S., Yucca Mountain offers lessons on technical, social and political aspects of selecting and constructing a used-fuel repository [24]. A summary of progress in other countries in characterizing, selecting, and constructing a DGR is given in [25].

In Canada, progress is being made on the licence application for a DGR near the Bruce nuclear site for Ontario Power Generation's (OPG) low- and intermediate-level nuclear wastes [26]. This facility will not accept used fuel. In a separate program, the Canadian used-fuel conceptual DGR design is based on the concept developed by AECL in the 1980s and 1990s [18-20] and subsequently refined by OPG and the NWMO [21]. The DGR concept is consistent with that developed by other international radioactive waste management organizations. It follows the requirements and guidelines provided by the federal government and the Canadian Nuclear Safety Commission (CNSC) on siting a DGR [27-29]. It is an engineered facility that uses a number of man-made and natural barriers to ensure that radionuclides are safely isolated from humans and the biosphere. Used fuel bundles would be sealed within long-lived copper containers, which would then be emplaced within chambers of an underground repository evacuated in a suitable crystalline or sedimentary host rock at a depth of 500 m to 1000 m. The rooms would be backfilled with clay-based sealing materials such as bentonite. After a period of

monitoring, the repository would be backfilled and sealed, but in such a way as to allow recovery according to the APM approach of the NWMO [11].

The DGR design reflects a defined and multiple-layered, defence-in-depth approach against the uncontrolled or inadvertent release and migration of radionuclides.

a) The ceramic UO_2 fuel pellets themselves are an excellent waste form for retaining the actinides and much of the non-gaseous and non-volatile fission products.
b) The fuel sheaths provide an additional barrier to the release of radionuclides, although this barrier is not usually credited in DGR performance assessments.
c) The reducing groundwater conditions at depth support the corrosion-resistance of the copper containers in which the used-fuel would be loaded for many thousands of years.
d) The bentonite clay acts as a porous plug, greatly inhibiting water movement through the repository and sorbing many actinides and fission products if they were to be released from the fuel matrix, the fuel sheaths and the copper container.
e) The host rock would chemically retain fission products and actinides.
f) And finally, the depth of the repository and its low groundwater flow rate provide a very large time delay to the migration of radionuclides to the surface.

The expected performance of the Canadian used-fuel DGR concept and similar repository designs from other countries have been extensively studied and modelled. Analysis shows that [19-23]:

- The additional risk of cancer for the most affected population is less than one in a million, up to a million years.
- Safety assessments carried out for the Canadian DGR concept predict a potential maximum annual dose to the most highly-exposed group living in a sensitive area near a DGR site in the future that is a thousand times lower than regulatory dose limits for a nuclear facility.
- The actinides are immobile and are negligible contributors to dose, even after hundreds of thousands of years.
- The main contributors to public dose (with assumptions that tend to maximize release) in the very long term are mobile, soluble and long-lived species (I-129 and Cl-36) which form anions in groundwater so tend to be repelled and not sorbed by minerals and clays. Their contribution to dose is a small fraction of the regulatory limit mentioned in the second bullet above.
- Natural analogues support the DGR design and predicted performance and illustrate the immobility of most radionuclides under the reducing conditions that would be present in a DGR. There are natural analogues for the behaviour of key features of a DGR: the uranium itself (such as the Cigar Lake uranium mine in Canada and the Oklo natural reactors in Gabon, Africa); the copper containers; and the bentonite-clay buffer material [30].
- The plan area of a DGR for 100,000 Mg of used CANDU fuel would be 5 to 7 square kilometres.

A description of how the chemistry of the engineered and natural barriers in a DGR would achieve the isolation of radionuclides from humans and the biosphere for very long periods of time is provided in [31]. Short-lived nuclides will decay to negligible levels before any breach of the copper containers. This includes tritium, Co-60, Sr-90, Y-90, Cs-137, Ba-137, Sm-151 and Eu-152. In addition, some of the actinides are also short lived, including U-237, Pu-241, Cm-242, Cm-243 and Cm-244. Many other nuclides have moderate to long half lives, and would be trapped in the UO_2 crystal lattice. Included in this category are many of the long-lived actinides (U-238, Pu-238, Pu-239, Pu-240, Pu-242, Am-241, Am-242 and Am-243), as well as Zr-93, Nb-93, Nb-94, Tc-99 and various isotopes of tin. Many elements in the used fuel, even if they were to escape the fuel matrix and the copper container, would form cations and be strongly sorbed by the clay buffer material and by the rock minerals, migrating little from a DGR. As already noted, some elements would be mobile and form anions and hence would not be sorbed by the clay buffer and rock minerals were they to escape from the fuel matrix and from the copper container. They include C-14, Cl-36 and I-129. They will, however, be isotopically diluted as they move through the geosphere and the biosphere. With its long half-life, I-129 is the largest contributor to dose from a DGR, although orders-of-magnitude lower than regulatory limits.

The size (and cost) of a DGR is largely determined by the decay heat from the used fuel or heat-producing waste, which determines the amount of heat-producing radionuclides that can be loaded into a container, the spacing of the containers in a placement room and the number and spacing of the placement rooms; e.g., cooler waste could potentially be packed more densely into fewer or smaller containers, which would have some cost savings. In most DGR concepts, there are temperature limitations imposed by the materials that can be used. In the Canadian concept, the temperature limit on the sealing materials surrounding the used-fuel copper containers is typically 100ºC. Fission products dominate the decay-heat production in the short term after discharge from the reactor (until about 100 years), while actinides (mainly plutonium) dominate decay-heat production in the longer term. To a first-order approximation, the decay heat for a given type of fuel (such as UO_2) will depend on the amount of the electricity that had been produced from the fuel. Hence, the larger quantity of used CANDU NU fuel is offset by its lower decay heat compared to higher-burnup used LWR fuel, and DGR costs for used CANDU NU fuel are similar to those for higher-burnup used LWR fuel [32, 33]. Increasing the storage time of the used fuel to a maximum of about 50 years before emplacement in the DGR would reduce the near-term decay heat source (i.e., largely due to fission products) and would decrease the DGR plan area and cost [34], beyond which there is negligible improvement largely due to actinide heating. Figure 1 shows the fission product and actinide components of decay heat from used CANDU NU fuel as a function of time after discharge from the reactor [35].

In the context of either direct emplacement of used CANDU NU fuel in a DGR or recycling, it must be understood that most of the used fuel is still uranium, which produces little decay heat. Removing the uranium alone from the used fuel would have little effect on a DGR, since the temperature limit on the containers is met by controlling the amount of heat-producing isotopes in the containers (whether short-lived fission products or long-lived actinides) and by adjusting the distance between the containers and the distance between the placement rooms in the DGR. The radiotoxic and heat-producing nuclides must be immobilized and diluted in a material that provides an effective barrier to their release in the DGR, and the UO_2, constituting 99% of the

used fuel, is an effective matrix. Removing the uranium would still necessitate immobilizing and diluting the fission products and the transuranic elements (TRU – plutonium and the minor actinides) in another matrix, such as borosilicate glass to maintain the temperature limits on the sealing materials, with little effect on the DGR design or cost [32]. So the used-fuel volume, per se, is not an effective metric for characterizing the back end of the fuel cycle.

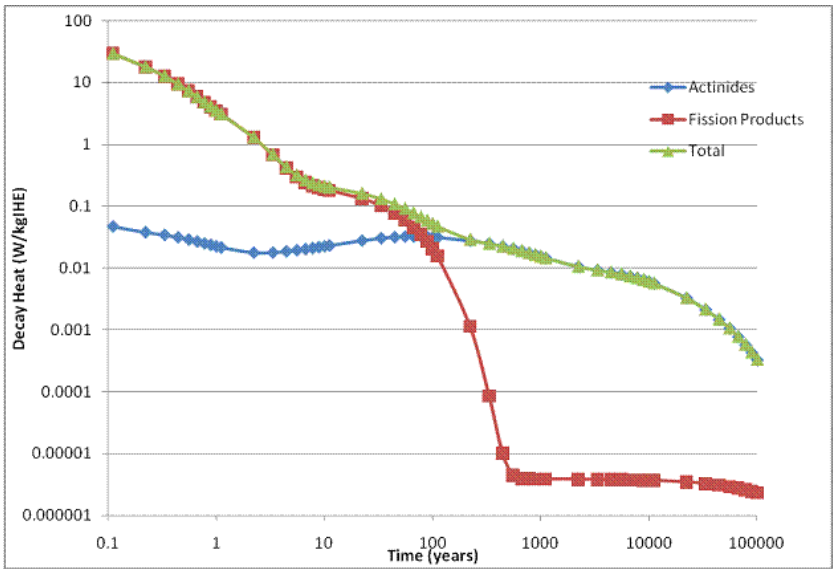


Figure 1: Decay heat from CANDU NU fuel as a function of discharge time from the reactor [35]

Radiotoxicity is a metric that characterizes the hazard from used nuclear fuel to humans from the radioactivity through internal exposure (either through inhalation or ingestion). Since the only way that the radionuclides in a DGR can reach the surface is through dissolution in water, ingestion radiotoxicity is often defined in terms of the volume of the water needed to dilute the radionuclides in the used fuel (or recycling wastes) to drinking water standards, or to some other reference or regulated dose limit. Alternatively, a relative index is sometimes used, where the radiotoxicity of the used fuel or recycling wastes is compared to a reference value. There is not a standard definition of radiotoxicity in use, although the term is widely used in discussions of P&T. Sometimes relative radiotoxicity is defined as the ratio of the volume of the water needed to dilute the radionuclides in the waste material to the volume of water needed to dilute an equal weight of uranium ore to the same standard. In this case, the concentration of the uranium ore will greatly influence the reference value. Yet another definition is illustrated in [36], which compares the radiotoxicity of used LWR fuel (or recycling wastes) to that from the uranium required to enrich the fuel (e.g., to uranium itself, not the uranium ore). Depending on how the reference radiotoxicity is defined, the time taken for the used fuel or recycle wastes to reach the reference value can change from a million years or so to thousands or hundreds of years. Hence, radiotoxicity is not an absolute metric, and its use must be treated with caution.

Most importantly, it must be appreciated that radiotoxicity is a measure of the potential hazard, not of the risk. It does not account for any of the engineered and natural barriers in a DGR designed to mitigate the release and movement of radionuclides to the biosphere. Radiotoxicity is akin to the source term in reactor safety analysis. Focusing on radiotoxicity can lead to

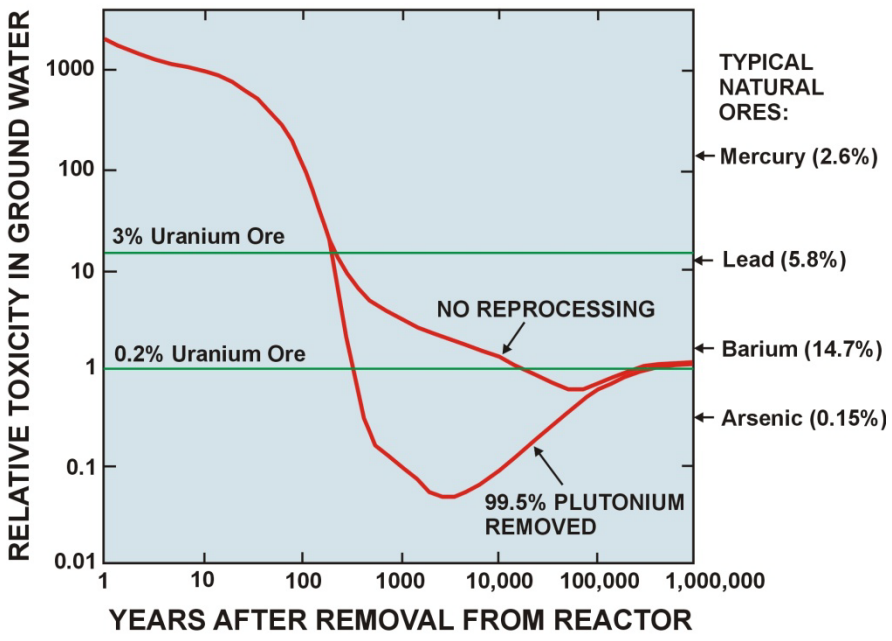
solution of the wrong problem. As has been discussed, actinides are immobile in a DGR with a reducing environment. While they are the largest contributor to radiotoxicity of the fuel after a few hundred years, they are negligible contributors to dose from the DGR. Reducing the long-term radiotoxicity of the fuel (for example through P&T) does little to reduce the long-term dose from the DGR, which comes from long-lived, mobile fission products such as I-129. In fact, P&T may decrease the long-term radiotoxicity while significantly increasing the short-term risk. Hence, dose, or risk, are more appropriate metrics to characterize the back end of the fuel cycle, rather than radiotoxicity.

Nonetheless, Figure 2, taken from [18], illustrates a number of important points. (Note that this analysis is over 30 years old, is for a lower fuel burnup than is currently considered, and is not as accurate as current calculations would be; however, it will be used for illustration on a qualitative basis.) Firstly, people make use of many materials that remain toxic forever, such as mercury, lead, barium and arsenic. The radiotoxicity of used nuclear fuel decreases with time, and after a few thousand years is less toxic than many of these ores. Secondly, radiotoxicity is not an absolute metric; changing the basis of comparison from a 0.2% uranium ore to a higher-grade ore containing 3% uranium reduces the time over which the hazard from the used fuel is higher than the corresponding ore, from hundreds-of-thousands of years to hundreds of years. If the ~20%-rich ores from Saskatchewan are the comparison, the period is even less. And finally, the figure illustrates that plutonium is the major contributor to the radioactive hazard after a few hundred years until the radiotoxicity falls to that of natural uranium levels.

It should be clear from this discussion that the direct emplacement of used CANDU NU fuel in a DGR is not an unsolved technical problem seeking a technical solution. While R&D continues on a number of technical issues [37], used CANDU NU fuel can be safely placed in a DGR using relatively common mining technology with extremely small risk to humans and the environment over a very long period of time. The major challenge appears to be in securing public understanding of the risks associated with the DGR concept and establishing a suitable process for siting a DGR. The NWMO is establishing such a process for siting a DGR in a willing host community [10].

The main driver for considering the recycling of used CANDU NU would thus appear to come from its energy value, rather than from a need to reduce the environmental impact of the used fuel or the size or cost of a DGR. Nonetheless, there are potential environmental benefits from used-fuel recycling relative to direct emplacement in a DGR. The predicted performance of a DGR is based on computer simulations (supported by tests and measurements as well as natural analogues) of a multitude of processes over hundreds-of-thousands of years. Establishing the credibility of these calculations, and convincing the regulator and the public of their suitability will be a challenge. Certainly, a probabilistic approach must be included along with a thorough uncertainty analysis. Reducing the time-at-risk would appear to lessen this challenge.

As shown in the next section, advanced recycling technology could also reduce the hazard and the decay heat in a DGR. Nonetheless, used-fuel recycling is not a magic bullet that would obviate the need for high-level waste disposal. Even with recycling, a DGR would be needed for disposal of the high-level waste from used-fuel processing.



Source: J. Boulton, Ed., "Management of Radioactive Fuel Wastes: The Canadian Disposal Program", AECL-6314, 1978.

Adapted for the Canadian Nuclear FAQ, www.nuclearfaq.ca

Figure 2: Relative toxicity (in ground water) of used CANDU NU fuel and natural ores [18]

3.2 Recycling of used CANDU NU fuel

The environmental impact of recycling used CANDU NU fuel would involve the entire fuel cycle, from the front end where less uranium would be needed, through used-fuel processing and recycle-fuel manufacturing, through disposal of the wastes created during used-fuel processing, to the management of the irradiated recycled fuel, including the possibility of multiple recycling. The environmental impact will depend on the details of the recycling process, which will create chemical and radioactive (low-, intermediate- and high-level) wastes. Such an analysis has not been performed in the context of recycling used CANDU NU fuel.

The environmental aspects of recycling used CANDU NU fuel can be considered from two perspectives:

1) is there an environmental incentive for recycling used CANDU NU fuel, and
2) if not, and the recycling of used CANDU NU fuel is pursued for other reasons such as for resource extension, what are the environmental aspects that need to be considered.

As noted earlier, the principal driver for P&T is to reduce the period of the perceived hazard of the long-term radiotoxicity of the radionuclides in a DGR, relative to some reference, from hundreds-of-thousands or millions of years to a few hundred or thousands of years and to reduce the decay-heat load [36, 38, 39]. Reduction of the long-term radiotoxicity appears to be motivated by the belief that public acceptance of nuclear power would be enhanced by reducing the long-term burden on future generations of nuclear fuel waste management. Also, reducing the decay heat would decrease the plan area of a DGR.

To achieve the orders-of-magnitude reduction in long-term radiotoxicity that is the goal of P&T requires:

- very high efficiency in separating plutonium (reduction factor in the order of 1000) and americium (reduction factor in the order of 100) in the used fuel;
- manufacturing, transporting and handling of highly radioactive and radiotoxic fuel and targets; and
- irradiating in fast reactors for long periods of time with multiple recycling and near-complete fissioning of the plutonium and minor actinides.

While steady progress is being made in R&D in these areas, the technical challenges are nonetheless daunting, and it is not clear that they can be overcome. Note that only fast reactors can fission all of the plutonium and minor actinides and achieve their near-complete destruction. All of the actinides can fission in a fast spectrum, albeit over long time periods, whereas in a thermal reactor, only some of the odd-mass-number actinides have sizeable fission cross sections. (This is illustrated in Figure 3, from [40]). The reduction of the long-term radiotoxicity and heat load of the recycling wastes comes at the expense of: a shorter-term increase in radiotoxicity and heat load; a shorter-term increase in the overall risk and collective worker dose; and, particularly in a thermal reactor, at the expense of neutron economy and fuel utilization. The burden on future generations would still extend to hundreds of years with P&T for the continual recycling of the actinides with a sizeable increase in radiotoxicity if the process were stopped.

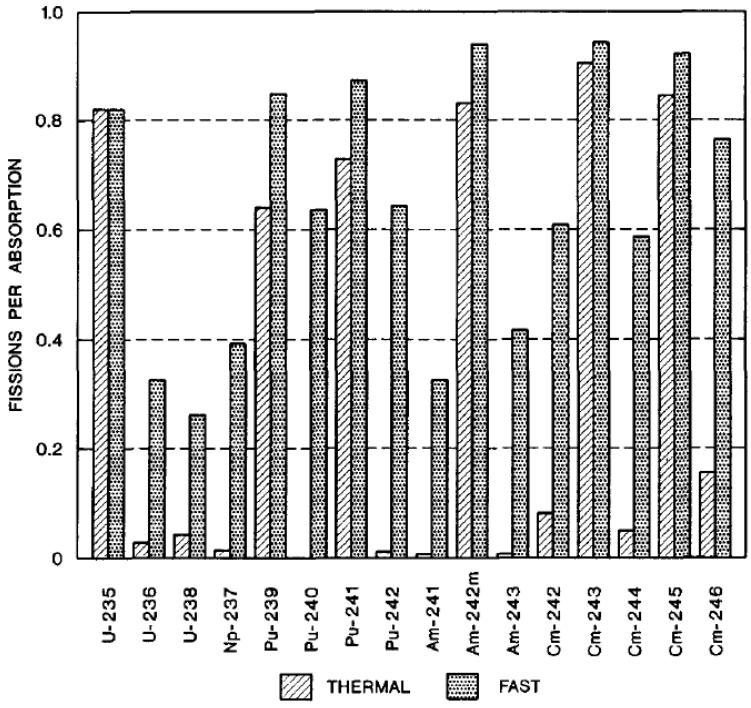


Figure 3 Probability of fission per neutron absorbed, for actinide isotopes in thermal (LWR) and fast spectra [40]

One can perhaps understand the interest in P&T in some countries. For example, the attempt to obtain political and social acceptance of a DGR at Yucca Mountain has failed [24] and the capacity of Yucca Mountain would have been insufficient for all of the used LWR fuel in the U.S.; smaller countries have limited geologies and resources appropriate for a DGR; some countries have already made large investments in reprocessing plants; some countries have limited fuel resources and wish to employ used LWR fuel recycling either in thermal or fast reactors for resource extension, in which case additional environmental benefits may accrue from P&T; and some countries envisage difficulties in finding willing host communities for a DGR.

The long-term radiotoxicity and decay heat of used CANDU NU fuel is dominated by plutonium after a few hundred years (Figure 2). Recycling the plutonium simply transfers this radiotoxicity to the recycled fuel. The recycling of TRU elements (plutonium and minor actinides) from used CANDU NU fuel in a CANDU reactor could achieve a two- to three-fold reduction in the radiotoxicity and heat load of the resultant waste – not a reduction of a hundred- or thousand-fold. Recycling these heat-producing TRU elements in the used CANDU NU fuel and allowing some decay of the fission products before disposal could reduce the size and cost of a DGR. For example, 40-70% of the TRU elements from used LWR fuel could be consumed in a CANDU reactor (depending on whether the TRU is mixed with uranium as MOX fuel or with an inert matrix), which would result in a similar reduction in the decay heat after 1000 years [5, 6]. Similar consumption rates could be expected for TRU from used CANDU NU fuel, although that analysis has not yet been performed. Similarly, utilizing plutonium as the fissile driver in a Pu/Th MOX fuel cycle could consume more than 50% of the plutonium in a single cycle, while minimizing the production of additional plutonium and higher-mass actinides, compared to recycling as plutonium-uranium MOX fuel. The net effect of used-fuel recycling on a DGR would also have to consider the evolution of radiotoxicity and decay heat of the used recycled fuel and processing wastes (whether recycled once or several times). The net consumption of TRU could reduce the long-term radiotoxicity and the decay heat in a DGR, depending on the recycling scheme.

Some of the minor actinides could also be recycled and transmuted, either in separate targets, or as part of the plutonium fuel mix. Keeping some fission products or minor actinides with the recycled plutonium would increase the proliferation-resistance of the material, at the expense of higher manufacturing and handling costs and reduced fuel utilization. The specific strategy would affect the decay heat and radiotoxicity of the irradiated recycled fuel.

As noted earlier, 99% of the heavy element mass of used CANDU NU fuel is comprised of the original uranium. Its recovery would have no economic value. So the treatment of the uranium from used CANDU NU fuel processing would be a key consideration in managing the processing wastes from recycling. One option would be to recycle the plutonium (possibly with other minor actinides) and a sufficient amount of uranium to give the desired plutonium concentration in Pu/DU MOX fuel. The fission products (and actinides that were not recycled) would need to be diluted and immobilized. Vitrification in borosilicate glass is a technology from conventional reprocessing that is well established. Mixing the fission product and minor actinides with mineral powders, such as zirconolite, hollandite and perowskite to form “SYNROC” for encapsulation and disposal in the DGR is another option being developed [41].

An alternative approach would be to separate and purify the uranium from the used fuel and to dispose of it as long-lived low- or intermediate-level waste, which would be less costly than its disposal as high-level waste. In this case, the fission products and minor actinides would again need to be diluted and immobilized.

Finally, the uranium, in the form of UO_2, could be used as the matrix material for diluting and immobilizing a portion of the fission product and minor actinide waste for disposal. For instance, once the plutonium from used CANDU NU fuel were removed for recycling, some of the non-gaseous and non-volatile fission products and minor actinides could be converted back to an oxide powder and sintered into ceramic waste pellets and sheathed, similar to the DUPIC process [42, 43] and to the fabrication of SIMFUEL [44].

Any gaseous and volatile fission products released from used fuel processing would need to be captured and immobilized. Some of these may be allowed to decay before their disposal in a DGR, which could have a positive impact on the thermally-derived plan area of the DGR. One of the largest short-term contributors to decay heat is Cs-137, which could be such a candidate. This is another feature of the DUPIC recycling process [33]. Removing both the plutonium and the cesium from the high-level processing wastes would be expected to significantly reduce the heat load of the processing wastes in a DGR (although again, the impact of the used recycled material must be considered).

I-129 is the most important long-term contributor to dose in a DGR. It is discharged from current reprocessing plants and isotopically diluted in the environment. While environmental dilution is safe and results in tiny doses (whether now or in a million years), dealing with I-129 is still problematic. The high thermal fluxes in a CANDU reactor offer the possibility of its transmutation to a stable isotope through neutron capture. The effectiveness of the transmutation of both I-129 and Tc-99 in the high flux of a CANDU reactor was shown in [45] and should be re-examined.

In the end, the processing of used CANDU NU fuel and the (multiple-) recycle of plutonium would produce a quantity of low- and intermediate-level wastes, as well as high-level fission product and actinide wastes that would need to be immobilized and disposed of. The net impact on disposal, in terms of economics, decay heat, environmental impact, and collective dose to workers and to the public, would need careful assessment for the specific recycling, fuel and reactor technology being considered.

In assessing whether the recycling of used CANDU NU fuel could be driven by environmental considerations, the following is noted:

- the ceramic uranium matrix comprising 99% of used fuel is an excellent waste form for immobilizing the radiotoxic nuclides in a DGR;
- storing and disposing of used CANDU NU fuel has low risk in both the short and long term;
- the dose from a DGR is expected to be miniscule over very long timeframes;
- if recycling were done, there would be an additional risk during processing the used fuel, in that at some stage during processing the radiotoxic nuclides would be released from

the uranium matrix, at which point their mobility would be increased in the event of a process upset or an accident. Conceptually, used-fuel recycling adds a higher short-term risk to the small long-term risk of used fuel (or high-level waste) emplacement in a DGR. Of course, good engineering would minimize those risks, but this is the ultimate societal trade-off.

The authors conclude that there is not a strong primary environmental driver for recycling used CANDU NU fuel. In the Canadian context, resource extension (through maximizing the energy from recycled plutonium), rather than waste minimization would be the major driver for considering recycling of used nuclear fuel. Nevertheless, minimizing the environmental impact of the waste, both near-term and long-term, from used CANDU NU fuel processing and from subsequent recycling would be an important consideration, and in fact, there are potential environmental benefits that could be realized.

4. Recycling technology and recycle-fuel manufacturing

The high radioactivity of used nuclear fuel will require shielded facilities for processing, and depending on the form of the recycled fuel, for fuel manufacturing, transportation and handling at the generating station. This will greatly increase the cost of recycled fuel as compared to CANDU NU fuel and will increase worker collective dose.

Conventional reprocessing uses nitric acid to dissolve the used fuel and solvent extraction to separate the uranium and plutonium from the minor actinides and fission products. Uranium and plutonium are separated with very high purity and low radioactive contamination from fission products and minor actinides. CANDU fuel elements and bundles have been fabricated from RU and from plutonium (i.e., as MOX) from the conventional reprocessing of used LWR fuel, for irradiation testing in the NRU reactor and reactor physics testing in the ZED-2 critical facility. No special precautions were required for handling of the RU fuel bundles. MOX fuel is fabricated at AECL's Chalk River Laboratories in glove boxes in the Recycle Fuel Fabrication Laboratory (RFFL) [46], and the MOX fuel can be handled with gloves.

Because of concerns over conventional reprocessing (i.e., its high cost, the use of large volumes of liquids and proliferation risks from separated plutonium) alternative methods are being explored for recycling used LWR fuel that are less expensive, simpler and have a higher degree of proliferation resistance. Many of these are dry or involve only a small quantity of liquids. The focus of many of these technologies is actinide management through P&T, so they involve the removal of plutonium along with one or more of the minor actinides. The minor actinides are intended to be fabricated into minor actinide fuels (containing plutonium) or targets for reactor transmutation. This has been the focus of the Advanced Fuel Cycle Initiative in the U.S. [47]. While fast reactors are envisioned for the ultimate destruction of the minor actinides (and possibly accelerator-driven systems (ADS)), as noted earlier the CANDU reactor has been shown to be complementary as an intermediate thermal consumer of TRU, thereby significantly reducing the number of fast reactors that would be needed [5-7]. The high thermal flux in a CANDU reactor enables significant consumption of plutonium and americium.

The regular Information Exchange Meetings on Partitioning and Transmutation (IEMPT) and the GLOBAL Conferences focus on advanced fuel recycling technologies and on P&T [48]. In general terms, these technologies would separate the uranium up front and decontaminate it for subsequent treatment either as long-lived low- or intermediate-level waste or for recycling (either directly into a CANDU reactor or for re-enrichment for LWR fuel). Some of the fission products would be separated and immobilized and some minor actinides either separated alone (for transmutation targets) or with plutonium (as transmutation fuel). The remaining fission products and minor actinides would be immobilized as high level waste.

When considering the application or development of advanced recycling technology for used CANDU NU fuel, the characteristics of the fuel and the application need to be carefully considered. The amount of fissile material available for recycling from used CANDU NU fuel is one-fifth of that in used LWR fuel, so the technology will need to be much simpler and cheaper and able to handle a much larger volume of material than that for used LWR fuel. This would imply a large industrial infrastructure to recover <0.4% of the material from the used CANDU NU fuel and to immobilize the remaining waste. As noted, the uranium has no residual value. A key consideration would be ensuring suitable proliferation resistance of the recycled plutonium, without excessively degrading its neutronic value through parasitic absorption. This could be accomplished by leaving a low neutron-absorbing fission product or minor actinide with the recovered plutonium, at the expense of requiring remote fuel handling. An opportunity not yet sufficiently exploited is the selective removal of radionuclides for medical or industrial application.

While AECL has not assessed the applicability of advanced recycling technologies to used CANDU NU fuel, it has looked at the application of some advanced technologies for recycling used LWR fuel into a CANDU reactor. Some of these technologies have features that might be applicable to the recycling of used CANDU NU fuel. For instance, the DUPIC process was developed jointly by AECL and the Korean Atomic Energy Research Institute (KAERI) as a simple, proliferation-resistant, dry technology for recycling used LWR fuel into CANDU fuel [42, 43]. It involves a series of oxidation/reduction cycles to convert used LWR fuel pellets into powder, which would then be sintered into CANDU fuel pellets and inserted into new CANDU fuel sheaths. Some gaseous and volatile fission products would be driven off during the processing. AECL fabricated three full-length CANDU fuel elements using the DUPIC process and irradiated them in the NRU reactor at the Chalk River Laboratories. While DUPIC would not be applicable to recycling used CANDU NU fuel because of its low fissile content, the fabrication and irradiation illustrate the advantages of the simple design of CANDU fuel and its small size and weight in remote fuel processing, manufacturing and handling. Individual steps in the DUPIC process could be applied to other advanced recycling technologies for recycling of used CANDU NU fuel, such as: removal of the pellets from the fuel sheaths; the high-temperature oxidation/reduction steps, which could be applied at the front end to convert the used fuel pellets to powder; the capture and immobilization of some of the gaseous and volatile species during processing; and the reconstitution of powder into waste pellets through sintering followed by re-sheathing, which could be used to produce an effective waste form for disposal once the plutonium and other desired constituents were removed from the used CANDU NU fuel.

Fluoride volatility (FV) is an advanced recycling technology that could be considered for recycling used CANDU NU or thorium fuel [49-51]. The reactor physics aspects of using FV for recycling used LWR fuel into a CANDU reactor have been assessed [52]. In that application, the uranium from used LWR fuel would first be separated and purified and used as RU in CANDU. The plutonium would be removed with a small amount of uranium (~5%) and some of the fission products and minor actinides. This so-called "plutonium ash" stream would provide a burnup of ~60 MWd/kg in a CANDU reactor. A similar process, or modification thereof, could be applied to used CANDU NU fuel [49]. Of course, keeping many of the fission products and minor actinides with the separated plutonium would reduce the achievable burnup and resource utilization from the plutonium. The application of FV and its variants to used CANDU NU fuel is being further studied.

5. Reactor considerations

The recycle of plutonium, whether as uranium- or thorium-based MOX fuel, would have broad implications for the reactor. A fundamental question would be whether existing CANDU reactors could accommodate recycled fuel, or whether new reactors would be optimised and built. A detailed assessment showed that the CANDU reactors at the Bruce site could be used without changes to the reactor core to utilize plutonium/uranium MOX fuel for dispositioning plutonium from dismantled nuclear warheads [53].

If the main driver for considering used CANDU NU fuel recycling is resource extension, then it follows that the recycling should be done in reactors having resource utilization at least as good as current CANDU reactors, which have the best fuel utilization of any reactor in the world. The pressure-tube supercritical water reactor (PT-SCWR) is an evolution of the CANDU design that is currently in the pre-conceptual design stage. Its high thermodynamic efficiency (~50%) would lead to an inherent advantage in fuel utilization. However, the severe demands on materials performing in high pressure and temperature supercritical water result in challenges in achieving good neutron economy which offset the gain in fuel utilization arising from the high thermodynamic efficiency [54]. If these challenges can be overcome, the PT-SCWR would have advantages over the current CANDU design in utilizing recycled plutonium. As described in Section 2.1.2, the SSET is a concept that is intended to address the question of long-term resource sustainability using the CANDU reactor. This would require changes to the current CANDU reactor core to further improve the neutron economy. The SSET cycle in CANDU offers an alternative to fast reactor technology for ensuring long-term nuclear energy sustainability, particularly in Canada. Of course, a completely new reactor technology, such as fast reactors, could be introduced, but the investment would be enormous compared to adapting CANDU technology.

Some of the many considerations that would need to be assessed from the perspective of utilizing recycled fuel in a CANDU reactor are:

- selection and qualification (including validation) of design and safety analysis methods and codes;
- fuel design and qualification;

- core design, including reactor physics (fuel and lattice design, reactivity coefficients, fuel management, static and transient analysis), thermalhydraulics, control and shutdown;
- safety and licensing;
- effect of radioactivity of fresh and irradiated fuel on fuel storage and handling and on dose to components and to personnel;
- impact of change in decay heat on used-fuel storage, both under water and dry; and
- criticality safety.

These assessments would be lengthy and costly, even without changes to the reactor design.

6. Safety and risk evaluation

Safety issues and risks associated with used-fuel recycling will need to be considered for the entire fuel cycle from mining to the disposal of recycle wastes and management of recycled fuels (e.g., their further recycling or emplacement in a DGR). These will be very much technology- and scenario-dependent. Used CANDU NU fuel is self-contained, the radionuclides are largely immobile and its direct emplacement in a DGR poses an extremely low and well-understood and -characterized risk to the public over the long term.

The separation of the used fuel into various components that would then be processed fundamentally changes the nature and timeframe of the system risk. There will be a new short-term risk from recycle-fuel processing, manufacturing and handling at the reactor, as well as a long-term component from the disposal of the recycle wastes and from the subsequent management of the irradiated recycled fuel. The fuel processing and recycle-fuel manufacturing plant would need to consider not only conventional safety risks (such as from fire, explosion, chemical and pressure), but the added collective public- and worker-exposures and risks due to radiological hazards. In this context, the radiotoxicity of the various process streams (both for inhalation and ingestion) represents a radiological source-term in accident analysis (that is more useful than radiotoxicity itself as a metric for a DGR). Separating the used fuel into components will increase the mobility and concentration of the radionuclides at times during processing, which will inevitably increase the short-term risk to workers and to the public. Of course, the processing and recycle-fuel manufacturing facilities would be designed to limit that risk. For advanced recycling technologies, the process flow-sheets for both fuel processing and recycle-fuel manufacturing have not been established with sufficient detail to estimate the safety and risk with confidence. For potential CANDU NU or thorium fuel recycling, these processes have not yet been defined.

The collective dose to workers from fuel recycling will have to consider the increased handling of radioactive materials from:

- fuel processing;
- recycle-fuel manufacturing;
- waste processing (e.g., vitrification, packaging);
- transportation and handling at the reactor; and

- waste management.

Public dose from these same activities will have to be addressed. Of particular interest will be the collective dose from the fuel processing and recycle-fuel manufacturing facilities and the dose from a DGR with recycle-fuel wastes. As noted previously, it will be important to quantify uncertainties that affect the DGR performance, and a probabilistic approach would need to complement a best-estimate of public dose. Given the complexity of the dose calculations, and the need for detailed information on the processes and material characteristics of the waste forms, it would be useful to establish a simplified performance metric for use in scoping studies to characterize the expected DGR performance for different recycling options. This might reflect, for instance, the solubility of the radionuclides and their radiotoxicity.

7. Non-proliferation and safeguards

A major consideration in fuel cycle design and operation is ensuring proliferation resistance. This term refers to both the intrinsic features of a fuel cycle that provide a barrier to diversion of fissile material, as well as the ease with which external measures can be applied to augment these barriers. External measures typically focus on international "safeguards", referring to engineered systems to contain and monitor the fissile materials. Non-proliferation and safeguards is an important and sensitive topic that applies to all aspects of the fuel cycle, from the front end, through the electricity-generating phase in the reactor, to the back end. Fuel cycle facilities and technologies have degrees of proliferation resistance; proliferation-resistance is usually not black-and-white. In general, safeguards can be applied to any facility and technology, but some facilities and technology are easier to safeguard than others.

While used nuclear fuel is considered to have a high degree of intrinsic proliferation resistance, partly due to its radioactivity – the so-called "spent fuel standard" [55] – the self-protecting radiation of used fuel decays with time in a DGR. However, the sealed repository would provide a significant amount of physical protection.

Recycling of plutonium in used nuclear fuel would result in a reduction in the quantity of plutonium, which is a positive action from the perspective of proliferation resistance. The "weapons-usability" of the plutonium would also decrease because of the increased production of higher-mass, even-number-mass non-fissile plutonium isotopes with a corresponding reduction in fissile Pu-239.

Technology developed for recycling of used CANDU NU fuel in Canada should not involve separated plutonium. Nor should the processing be easily alterable to allow its separation. One step towards this would be the inclusion of fission products having penetrating gamma radiation as a proliferation barrier. This would significantly increase the cost of recycle-fuel fabrication since a shielded facility would then be required. How proliferation concerns are met will affect both the energy potential from the recycled plutonium, if neutron absorbing isotopes are included with the recycled plutonium, and the cost of recycling.

With the thorium cycle, the self-generated fissile U-233 is accompanied by U-232, which decays to daughter products with significantly energetic gamma rays. This would provide a strong

proliferation barrier shortly after uranium separation. Again, this would require remote fabrication in a shielded facility. In recycling the uranium, proliferation resistance can be increased by adding U-238 to "denature" the recycled U-233. This would reduce fuel utilization (the SSET cycle would not be possible), and produce a larger mass of minor actinides, including plutonium.

Increasingly, proliferation-resistance considerations take into account the geopolitical architecture that is associated with the fuel cycle; that is, it matters where the fuel is being manufactured or recycled, and who is doing it [56]. These considerations are becoming more important globally as the number of deployed reactors and states with reactors increases out of step with the resources needed to apply traditional safeguards to all of them. Canada is officially recognized as a low proliferation risk by the International Atomic Energy Agency (IAEA) and is currently operating under a more efficient and less intrusive safeguards regime because of this [57]. If there are to be a limited number of approved states deploying advanced fuel cycle manufacturing and recycling technology, then it may be logical to assume that Canada should be one of them. The combination of high-proliferation-resistant technology and controlled technology deployment would provide the necessary level of assurance against diversion of fissile materials as demanded by the international community.

8. Economics

For the recycling of used CANDU NU fuel to be economical with the once-through fuel cycle, the total levelized unit energy cost of the two cycles should be comparable. An appropriate economic metric is then the break-even cost of NU where the levelized unit energy cost for recycling CANDU NU fuel equals that for the once-through NU fuel cycle. Given the present prospects for a significant growth in demand for mined uranium based on international plans for the growth of nuclear power, the price of mined uranium will likely increase significantly over the next 30 years. Nonetheless, given the very low cost of CANDU NU fuel currently, this will be a challenging metric to meet. In addition, the costs of base-load nuclear-generated electricity will need to be competitive with alternate means of electricity generation, all calculated on a present-value basis.

One basis for an economic assessment would be to consider the estimated 100,000 Mg of used CANDU NU fuel from the present fleet of reactors in Canada and the cost of either its direct emplacement in a DGR or its recycling to produce additional electricity. On the one side of the equation would be the cost of emplacing that used CANDU NU fuel in a DGR. The NWMO has estimated the costs of the APM approach for ~73,000 Mg of used CANDU NU fuel [8, 12]: "Project costs are estimated to be between $16 and $24 billion (2002 dollars); or $7-$8 billion in present value terms (January 2009$)." On the same side of the equation would be the total cost of producing electricity equivalent to that generated from the recycled material, using NU in existing (or new) CANDU reactors. This would include the cost of NU, conversion to UO_2, fuel manufacturing, electricity production, used-fuel storage and emplacement in a DGR. These costs are well established.

On the other side of the equation would be the total costs of recycling the plutonium from 100,000 Mg of used CANDU NU fuel. This would include all costs associated with the research, development, design, safety and licensing analysis, construction and operation of several facilities such as a used-fuel processing plant, used-fuel manufacturing plant, CANDU reactors using the recycled fuel (either existing or optimized reactors) and all of the relevant waste treatment and management facilities. (Multiple recycling would complicate the analysis.) Many of these cost elements are not known since the recycling technologies have not been established and a useful first step would be a parametric study to determine the break-even cost of NU against various assumptions for the recycling component costs.

Both sides of the equation would include the value from the electricity generated, but these terms may largely cancel.

Several organizations and programs have established methods and computer programs for fuel cycle economic analysis (e.g., see [58] for a recent analysis for LWRs). The Veeder and Didsbury report [14] includes an algorithm for calculating fuel cycle costs, using component costs as input. Initial analysis need not be sophisticated to gain an understanding of the economic challenge of recycling used CANDU NU fuel. A study for the NWMO recently applied updated estimates of the cost of conventional reprocessing of used LWR fuel to used CANDU NU fuel [13] and concluded that current reprocessing technology will clearly not be economical at the present time.

There are many challenges to the economics of used CANDU NU fuel recycling, as have been noted in this paper:

- the fuel cycle costs for CANDU NU fuel are very low and this forms the reference point against which the cost of recycling needs to compete;
- the quantity of recoverable fissile material in used CANDU NU fuel is about a factor of five lower than in used LWR fuel; the processing cost of current technology is proportional to the amount of heavy element processed, so the cost of the fissile material recovered from used CANDU NU fuel using current technology will be about a factor of five times the cost of that from used LWR fuel;
- if remote fuel fabrication and handling is required because of the addition of fission products to the recycled plutonium to enhance its proliferation resistance, then this will further increase the cost of using recycled fuel;
- once the plutonium is recovered for recycling, the remaining nuclear waste would be almost the same mass as that of the current used CANDU NU fuel.

Clearly, a new used-fuel processing technology would be needed, tailored to the characteristics of used CANDU NU fuel.

An economic analysis would show the cost targets for used CANDU NU fuel processing technology and recycle-fuel manufacturing as a function of the price of NU. It would also provide insights into the future competitiveness of nuclear energy relative to other energy sources and would allow a comparison of the cost of plutonium recovered from used CANDU NU fuel to the cost of fissile extraction from other sources, such as from used LWR fuel, from

fast breeder reactors, from depleted uranium tails, and even from uranium extracted from sea water.

Finally, if recycling of used CANDU NU fuel were found to be viable, then a business model would be needed to pull together the appropriate partners and collaborators for developing the technology, for building and operating the necessary infrastructure and for generating the necessary funding.

9. Public acceptance

The question of recycling used CANDU NU fuel needs to be considered in the broader context of nuclear energy sustainability, both globally and in Canada. Used fuel recycling would not be an end in itself, but rather a means towards achieving a sustainable nuclear energy future. It is in this context that the SSET cycle is suggested as an ultimate end-point for achieving resource self-sufficiency in Canada using CANDU reactor technology. We have the geology, natural resources, people, and technology for a made-in-Canada solution to nuclear energy sustainability. However, nuclear sustainability is not an objective at any cost – it must be competitive with other energy options.

Regional fuel cycle facilities are being considered elsewhere in the world, particularly in Europe, but a North-American approach to nuclear sustainability has not been considered in this paper because of the obvious social and political challenges of transporting used nuclear fuel across international borders.

While fuel cycle considerations are global in nature, fuel cycle solutions need to be tailored to meet the local situation. The approach taken in Canada must be cognizant of international fuel cycle activities and benefit from international R&D, but must reflect the Canadian reality, which will be different from the circumstances in other countries. There isn't a one-size-fits-all solution to the nuclear fuel cycle. As was stated over ten years ago [59], "The fuel-cycle path chosen by a particular country will depend on a range of local and global factors. The CANDU reactor provides the fuel-cycle flexibility to enable any country to optimize its fuel-cycle strategy to suit its own needs." The CANDU reactor provides a compelling synergism between LWRs and fast reactors, and can contribute substantially to global nuclear sustainability, quite apart from the consideration of recycling used CANDU NU fuel.

The considerations in this paper on recycling used CANDU NU fuel may apply to other countries having CANDU reactor technology, although the conclusions may be different. Countries having both CANDU reactors and LWRs would recycle their used LWR fuel before recycling used CANDU NU fuel because of the higher fissile content of the former, and may very well consider recycling used LWR fuel into a CANDU reactor. A country having a small CANDU reactor fleet will likely not be able to justify the large investment required for used fuel recycling. The set of circumstances in Canada favors considering the option of recycling used CANDU NU fuel.

The public would ultimately have to accept used nuclear fuel recycling, not only on a broad societal basis, but on a local basis by any communities directly affected by the associated facilities and industries. There is societal acceptance of the need and benefit from recycling in our everyday lives. That same philosophy could apply to nuclear energy; that is, maximizing the energy from our nuclear fuel resources while minimizing the environmental impact. It is encouraging from NWMO's extensive public dialogues that many members of the public frequently expressed the view that used fuel is a valuable resource and that "science will find a way" to recycle it. The APM strategy was to some extent a positive response to that view.

Many social aspects need to be considered. The long half-life of some radiotoxic nuclides in used fuel is sometimes seen as a barrier to public acceptance of nuclear power and yet our society uses many toxic materials and metals that do not decay. On the other hand, some have expressed concern that after a few hundred years, the radioactivity from the used fuel will have decayed to a level where self-protection no longer provides sufficient proliferation resistance, and a DGR would become an accessible plutonium mine. Recycling of plutonium and minor actinides in a CANDU reactor would not substantially reduce the long-term radiotoxicity of the radionuclides in a DGR. The estimated long-term risk from a DGR is already exceedingly low. Will the current generation accept an increased short-term risk and increased collective dose if recycling were to move from conceptualisation to reality? Will the industry be better able to communicate to the public the nature and level of the short-term risk from a fuel recycling and manufacturing plant as compared to that from once-through used fuel or high-level wastes in a DGR? Would the public view the use of nuclear energy as greener, more environmentally friendly, and more acceptable if used nuclear fuel were recycled? Would the public have a positive view towards the economic and employment benefits from a "recycle energy centre" associated with a DGR? Would the public embrace a "waste-to-energy" approach embodied in recycling of used nuclear fuel?

The recycling of used nuclear fuel should not be positioned as an alternative which can avoid the need for a DGR for nuclear fuel wastes. The nuclear industry must clearly communicate that used-fuel management, including ultimate emplacement in a DGR is technically sound, economically viable and safe. There is no contradiction in assessing the viability of recycling used nuclear fuel as a resource for further energy production as a parallel activity.

Public acceptance will be a pre-requisite to obtaining political support for any new nuclear energy initiative, whether new nuclear power plants or used-fuel recycling. In this regard, industry has a role to play in communicating with the public, if indeed it is determined that recycling of used CANDU NU fuel is warranted. Since electricity is under provincial jurisdiction in Canada, provincial governments, in concert with utilities and industry proponents would play a key role in decision making. The discussion on used nuclear fuel recycling would need to be taken in the broader context of sustainable energy supply, involving both nuclear and non-nuclear options, in Canada and internationally. The adoption of wind- and solar-energy initiatives is only possible, considering their very high levelized unit energy costs compared to those of hydraulic, fossil, and nuclear energy, because of government policies that encourage them on the basis of perceived long-term societal gain, in line with perceived societal values supporting green energy. Initiatives to curb global warming will also be driven by public policy decisions, which reflect broad societal concerns over this issue, irrespective of its real cause.

10. Conclusion

The energy potential from the plutonium in used CANDU NU fuel is very large. Used-fuel recycling warrants renewed examination given the past experiences and maturing of the nuclear industry, the rising costs of limited energy resources, the long-lead times to develop and build efficient and safe infrastructure and the time necessary to address the societal and political demands. The realization of the full energy potential of the plutonium would require increased attention to neutron economy in the reactor core and fuel design, so that fuel utilization is not compromised through parasitic absorption. The direct emplacement of used CANDU NU fuel in a DGR following the APM approach is safe, with a miniscule risk to man and the environment. The recycling of plutonium (and minor actinides) from used CANDU NU fuel into existing or new CANDU reactors would not appreciably reduce the long-term radiotoxicity or risk from the residual nuclear waste or the time during which the waste is hazardous. Nonetheless, recycling used CANDU NU fuel could be designed to yield broad environmental benefits.

The low concentration of plutonium in used CANDU NU fuel, coupled with the lack of economic value of the contained uranium, means that a new recycling technology would be needed, aimed specifically at the characteristics of used CANDU NU fuel. The cost of used-fuel processing, manufacturing and remote handling will pose significant challenges to the economics of recycling, which would be partially offset by expected increases in the price of natural uranium over the next thirty years, driven by increases in demand by the expansion of nuclear-generated electricity in many nations.

The considerations in assessing the viability of used CANDU NU fuel recycling are many and complex. They are much broader than just technology alone and are inter-related with short- and long-term economics and socio-political policy. Any decisions are also dependent on the specifics of the recycling scenario. The assessment of used CANDU NU fuel recycling should involve a strong, coordinated approach from across many organizations (e.g., AECL, nuclear utilities, nuclear fuel industry, government departments and agencies, universities and public-policy institutes). The required technology is technically complex and expensive, and international collaboration would be required from initial R&D to industrialization.

This paper identifies the key factors, and provides a framework for assessing the recycling of used CANDU NU fuel in the Canadian context.

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