Productive Elimination of Nuclear Waste (PENW): A Complementary Boon for CANDUs and the Canadian Nuclear Industry

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Abstract

Spent CANDU fuel with its substantially lower fissile content than spent LWR fuel is currently considered waste, slated for long-term permanent DGR disposal. Nevertheless, it is over 99% heavy atoms all of which can be used as fuel in fast-neutron reactors (FNRs). Such use extracts 13,400% more energy, and by splitting the constituent long-lived transuranics also eliminates their long-term radiotoxicity. FNR fuel cycling was achieved for decades elsewhere. Its adoption now for spent CANDU fuel should produce a win-win for the Canadian nuclear industry: effectively no deleterious long-term radioactive legacy, an easy justification for more CANDU reactors, and a bright future.

1. Introduction

Canada's stored used CANDU fuel stands currently at 48,500 tons, increasing about 1400 tons per year [1]. It is considered "waste", and slated for permanent disposal in a planned deep geological repository (DGR) 500 to 1000 m underground in Canadian Shield granite or in Ordovician sedimentary rock. Other nations with civilian nuclear power reactors are likewise planning to discard their used fuel similarly in locally available geological strata: e.g. granite in the Czech Republic and in Spain, clay in Belgium, or salt in Germany [2].

The impetus for this approach is the long-term radiotoxicity of the used fuel engendered by the transuranic actinides, the plutoniums, americiums, curiums, etc., heavier atoms created in the reactors primarily from uranium-238 in the fresh fuel (see Figure 1). The radiotoxicity of those atoms is about 1000-fold higher than natural uranium, and does not decay back to levels of uranium for over 400,000 years. While most of the fission products decay before 300 years, a few, at relatively low levels of radiotoxicity, also have very long lifetimes. Since some of them, such as iodine, are biologically important, it has been deemed prudent that all of the used fuel must be sequestered from the biosphere to prevent potential risks of inadvertent ingestion.

Nevertheless, it is somewhat puzzling that such a thrust to discard the used fuel has gained a huge international momentum, considering that the used fuel still has an energy content of over 95% in the case of light-water reactors, and over 99% for CANDU reactors, in terms of the respective content of heavy atoms. It has been shown since the 1960s that much more of this fuel can be converted to energy in fast-neutron reactors (FNRs). With additional fuel cycling all of the energy can be extracted, with the

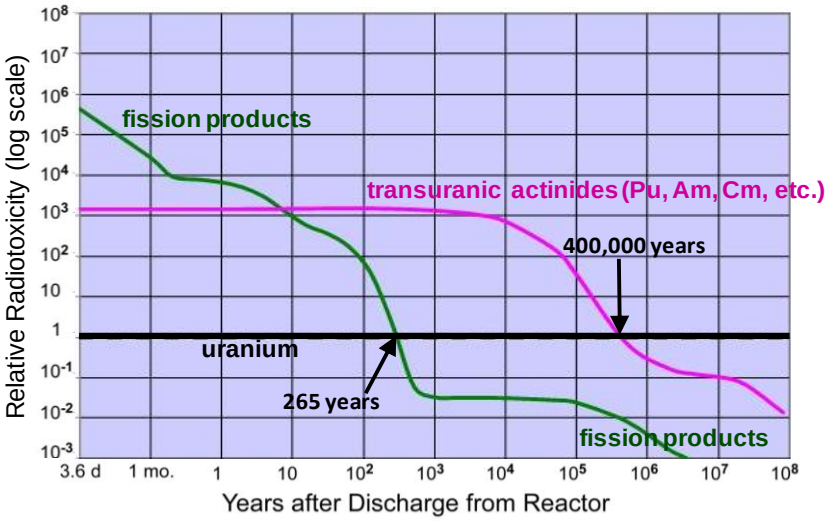

Figure 1 Evolution of Radiotoxicity from Used CANDU Fuel Components Relative to Natural Uranium.

Elimination of the transuranic actinides in fast-neutron reactors and extraction of uranium would result in a huge reduction in radiotoxicity of used fuel waste, about 42,000X per unit time at 1000 years, and also shortens the time of decay to background levels of natural uranium from 400,000 years to 265 years. After 265 years the radiotoxicity of the fission products is lower than that of the natural uranium in the CANDU fuel from which they are created in the reactor. The term radiotoxicity is used throughout this paper since it incorporates the roughly 20-fold larger biological effect of alpha emissions versus beta and gamma emissions at equivalent energies compared to the use of the term radioactivity. Note the log scales of both axes.

additional bonus that the long-term million-year radiotoxicity of the transuranic actinides can be eliminated as these atoms are fissioned.

Elimination of the long-term radiotoxic elements in used reactor fuel while extracting energy would remove one of the major concerns in the general population against the acceptance and expansion of nuclear power, a non-carbon energy source that could have a massive impact on lowering greenhouse gas emission for many centuries. This potential alternative to a DGR is examined in some detail below.

2. The Fast-Neutron Alternative

The Russian commercial BN-600 FNR, running since 1980 at a power of 600 MWe, refuels after a burnup of around 11%. The US EBR-II, with an output of 20 MWe from 1964 to 1994, achieved burnups up to 20% [3]. Experimental fuel canisters of the EBR-II fuel type were tested in the French Phenix FNR (250 MWe, 1973-2009) to a burnup of 25% without failure of the fuel pin [4]. This level

of burnup approaches a theoretical burnup limit of 35% due to neutron absorption from the build-up of fission products as irradiation in the reactor proceeds (Fig. 2) [5].

Recycling of the used FNR fuel after extraction of the fission products (FPs) permits complete utilization of the heavy atoms ideally, with reported TRU losses of 0.1% or less [6], leaving virtually

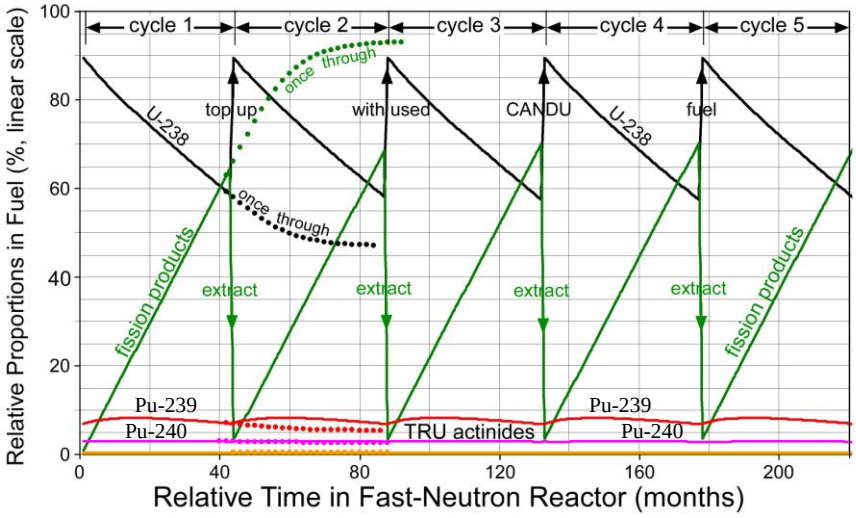

Figure 2 Consumption of uranium and behavior of fission products and of other actinides. Concentrations of heavier transuranic actinides such a Pu-241, Pu-242, Am-241, Am-242, etc., are too low to be shown usefully on this scale, and crowd into the horizontal axis.

only fission products, most of which decay in less than 300 years. Recycling was carried out in the EBR-II for 35,000 fuel pins, or the equivalent of 5 full reactor core loads.

Therefore, if any used CANDU fuel is to be sequestered, why not first extract more or all of its 134-fold remaining energy content in fast-neutron reactors? The environmental and financial implications would be enormous (see below). Moreover, the elimination of the long-term radioactivity of used fuel "waste", would eliminate a psychological block in the populace that in part is hindering the acceptance and growth of this huge non-fossil nuclear energy source.

Used CANDU fuel has the lowest fissile content compared to all other thermal reactor used fuels, about 0.23% U-235 and 0.27% Pu-239 plus Pu241 [7], making this fuel unattractive as a source of fissile material for recycling in thermal reactors. Nevertheless, extensive and complete energy extraction from all of the used CANDU fuel, including the U-238, is possible in FNRs, since FNRs maintain the fissionable content necessary for their operation, cycle after cycle (Fig. 2, [3]). Merely the heavy atom content equivalent to extracted FPs has to be replenished.

Used CANDU fuel with a 99% content of heavy atoms is a very appropriate replenishment. Its 0.74% fission products (FPs) are easily accommodated, since FNR fuel can function with a 10% FP content or higher, theoretically up to 35% (see Fig. 2). Of course shielded, remote manipulations would be

required, as they would in the cycling of FNR fuel itself. Shielded facilities are available at the AECL labs, now CNL, to be used, or to be duplicated elsewhere.

The re-use and cycling of used CANDU fuel in a fast-neutron reactor is examined below, starting with the potential value remaining in the CANDU fuel, considering fission product extraction from FNR fuel, and assessing the speed with which the currently stored CANDU fuel could reasonably be processed into FNR fuel.

3. The Potential of Used CANDU Fuel

In general, used nuclear fuel is considered a liability, since, having depleted its content of fissile neutron-replenishing heavy atoms, it is no longer considered fuel in thermal nuclear reactors. On the contrary, the used fuel is now suffused with highly radioactive fission products and transuranic actinides that require shielding and isolation from any biological environment.

Such isolation is sought in deep geological repositories (DGRs) planned in most countries with nuclear power. In Canada such a repository for 3.6 million used CANDU fuel bundles, built into granite of the Canadian Shield or into Ordovician sedimentary rock [7, p.133], is expected to have a life-time cost of $19.5 billion from construction to filling to decommissioning to a green-field state [8]. These funds are being collected in trust from electricity produced by nuclear power, with the fund in 2014 standing at $3.24 billion [9]. Sufficient funds have to be sequestered for the DGR process by the time that the last of the 3.6 million CANDU fuel bundles yields its energy in approximately 2028.

3.1 Used CANDU Fuel as a Resource

Fresh CANDU fuel in the form of natural uranium currently supplies about 50% of Ontario's electricity. In 2008, for example, 82,265 CANDU bundles or about 1480 tons of natural uranium were used to produce 115 billion kWh of electricity, worth $13.1 billion at current mid-TOU (time-of-use) prices of 11.4 ¢/kWh [7, p.351; 10]. This was achieved by fissioning only 0.74% of the heavy atoms in the fuel [7, p.341].

If it were possible, and it is, to fission all of the heavy atoms in the fuel to extract their energy, not just the 0.74% but also the remaining 99.26%, then 134 times additional energy could be obtained from the fuel. As of mid-2014 close to 2.51 million used CANDU fuel bundles have been accumulated at various reactor sites in Canada containing approximately 49,400 tons of heavy metal [1, p.19]. The total nuclear energy content remaining in those 49,400 tons would create

$$115 \times 10^9 \times 134 \times 49{,}400/1480 \text{ kWh} = 5.16 \times 10^{14} \text{ kWh of electricity.}$$

At Ontario's current mid-point TOU (time-of-use) price of 11.4 ¢/kWh this would fetch $58.8 trillion.

Since $13.1 billion worth of electricity was produced in one year, 2008, the $58.8 trillion of electricity would supply non-carbon nuclear electricity for about 4500 years at current levels of nuclear output.

By this measure, jettisoning the used CANDU fuel would not only cost the $19.5 billion for the DGR, but would forego the nuclear energy still in that "waste". The permanently closed DGR would irretrievably sequester fuel in it 3.6 million bundles with an extractable energy content equivalent to $84 trillion non-carbon electricity, or $2.37 million for every Canadian. Clearly it is worth considering the used CANDU fuel as a resource rather than as waste to be discarded.

3.2 Reduction of Long-Term Radiotoxicity

There is a further important advantage to the re-use of CANDU fuel to extract its energy: a massive reduction in its long-term radiotoxicity.

Figure 1 shows the relative radiotoxicity of used CANDU fuel in relation to the radiotoxicity of natural uranium in the fresh fuel bundle. It is clear that the long-term radiotoxicity is dominated by the TRUs, being about 1000 times higher than uranium for many millennia and not decaying to the uranium levels for about 400,000. This is the chief reason for sequestering the used fuel away from the biosphere in a DGR, since ingestion of such isotopes would be harmful.

However, if these TRU isotopes are fissioned to extract their energy, they cease to exist and their long-term radiotoxicity is eliminated. The heavy atoms, being split, become lighter atom fission products (FPs), about 70% of which are non-radioactive. The remaining 30% decay quite rapidly to levels below the radiotoxicity of uranium; only two, Sr-90 and Cs-137 require about 300 years to reach those levels. A few FPs, at levels well below uranium in radiotoxicity, have very long half-lives that result in the extension of the curve to longer times (Fig. 1). They will be discussed later.

Thus, considering used CANDU fuel as potential fuel in fast-neutron reactors would provide not only massive amounts of additional non-carbon energy, it would also result in a massive reduction in the long-term radiotoxicity of the used CANDU fuel.

4. Fission Product Extraction – Electrolytic Separation in Molten Salt

For the continuous cycling of heavy atoms through FNRs the fission product "ashes" have to be removed periodically, at the end of each fuel cycle.

Pyroprocessing is the recommended procedure for separation of FPs from heavy atom elements in the metal fuel rods of sodium-cooled FNRs such as the EBR-II or the PRISM (GE-Hitachi). It is an electrolytic separation in a mixture primarily of molten NaCl and KCl and small amounts of chloride salts of the different constituents of the used fuel [3,6].

In brief, the procedure starts by placing used FNR fuel rods, cleaved into inch-long pieces, into a steel anode basket in an electrolytic cell filled with the molten chloride salts at around 500ºC.

4.1 Actinide Separation

The actinides, including uranium, and most FPs in the used fuel, dissolve as chlorides at the anode. Of all the actinides and FPs only uranium plates out, virtually pure, at an iron cathode. Once most of the uranium has plated out, a second cathode of molten cadmium immersed in the salt collects all of the TRUs, the remainder of the uranium and a small proportion of the FPs.

It is not possible thermodynamically to obtain pure plutonium in this process, the plutonium being always mixed with uranium and the other TRUs as well as with a few highly radioactive fission products. As well, plutonium in its cycled form consists of a number of isotopes, of which Pu-239 and Pu-240 are shown in Fig. 2, with non-fissile Pu-240 plus Pu-242 being about 30% of the plutonium content. The TRU fraction from the cadmium cathode is thus self-protected on the one hand, and not in an isotopic form that can be readily made into weapons material, providing a relatively high level of proliferation resistance [3].

4.2 Fission Product Separation

The fission products are separated into three groups in this process. The noble gases and volatile FPs such as iodine are collected as vapours. The noble metals, such as rhodium, ruthenium, palladium, zirconium, etc., including the iron cladding of the fuel rods, do not dissolve, and either stay in the anode basket or drop to a molten cadmium bath below. The remaining FPs accumulate as chloride salts in the electrolyte since they do not plate out on the cathodes.

When the electrolyte becomes saturated with fission product chlorides, the remaining actinides in the electrolyte are "drawn down" electrolytically (using an empty anode) to clear them from the salts. Laidler et al. [6] indicate that the then-current "version of the pyroprocess features efficient (>99.9%) recovery of the actinide elements".

After extraction of the actinides the FPs are removed from the salts by the equivalent of chromatographic separation on zeolite columns. The salts are returned to the electrolytic cell for further re-use. Thus the pyroprocess, leaves very little extraneous process waste.

5. FNR Fuel Reconstitution

It is clear from Figure 2 that the heavy-atom content of transuranic actinides that are created in the reactor, represented here by Pu-239 and Pu-240, remains at the same concentration at the end of a fuel cycle as it was at the beginning of that cycle. Thus, once the neutron-absorbing fission products are removed from the used fuel, the fissionable content in the remaining heavy atoms is sufficient to restart the reactor without the addition of further fissile components.

The FNR fuel is reconstituted with the pure uranium from the steel cathode plus the mixture from the cadmium cathode, of uranium, TRUs plus some FPs. The mass of FPs removed in pyroprocessing can

be replaced by any source containing U-238 and other heavy atoms. For our purposes the replenishment of this missing mass can be and should be used CANDU fuel.

The uranium and other TRUs in the pyroprocess are in the form of metal and are melted together to cast new fuel rods. Used CANDU fuel first has to be reduced from the oxide to metal form. This can be and has been carried out using electrolytic reduction in the presence of lithium metal and lithium oxide [3, p.211]. All of the uranium as well as the other constituents of the used fuel are reduced in the process.

The metals from the reduced used CANDU fuel and those from the pyroprocess are then melted together in the appropriate proportions and cast into FNR fuel rods for the next fuel cycle. The procedure is sufficiently simple to be carried out by remote manipulation in shielded "hot" cells.

As will be mentioned below, the very low fission product content of the used CANDU fuel permits that more of the used CANDU fuel can be utilized in the reconstitution of new FNR fuel. This is possible if the pure uranium on the iron cathode of the pyroprocess is stored separately and not used in the new fuel. Its mass can be substituted just as well by used CANDU fuel, permitting a quicker reduction of the volume of stored CANDU fuel "waste".

6. Used CANDU Fuel Pre-Processing

The primary goal of pyroprocessing is the clean separation of fission products from used nuclear fuel. The procedure at the same time separates pure uranium and a combined mixture of uranium with TRUs and a residue of fission products. All of any given batch of used fuel must be processed in its entirety to obtain the three fractions.

For used CANDU fuel the constituents of greatest radiotoxic concern are the long-lived TRUs. Their extraction, even in impure form would permit their preferential use in FNRs resulting in a quicker reduction of their radiotoxicity in the used fuel. However, the fraction of TRUs in CANDU fuel is only 0.4%, making their isolation by pyroprocessing a relatively inefficient and consequently costly process.

A relatively simple procedure, based in part on current production of uranium oxide from yellowcake (uranium trioxide) by the company CAMECO [10] can pre-extract about 90% of the uranium, leaving a 10% fraction with all of the TRUs and fission products.

Just as uranium trioxide is dissolved in nitric acid as the first step to purify the ore [10], used CANDU fuel can be similarly dissolved. The constituents, primarily uranium, are turned into nitrates which are very soluble at high temperature. Lowering the temperature causes crystallization of the high concentration of uranium nitrate. At 0ºC approximately 90% of the uranium nitrate will crystallize out [11,12], while at most about 1% of the fission products are entrained in the crystal mass. A recrystallization of the uranium nitrate crystals from clean hot water would provide further purification.

Denitration, and calcining at 600ºC, [12,13] turns both the uranium nitrate crystals and, separately, the remaining 10% mass of uranium-depleted used CANDU fuel back into oxide form. The volatile

products are captured. Oxides of nitrogen are reconstituted into nitric acid for re-use, while volatile FPs are secured for further processing (see discussion of iodine, below).

The 10% fraction of the mixture of uranium, FPs and TRUs, now more concentrated, provides a more efficient input into electrolytic separation by pyroprocessing or into FNR fuel refabrication.
The pre-processing of used CANDU fuel by uranium nitrate crystallization has the result of reducing the capacity requirement for pyroprocessing by a factor of 10. This becomes an important consideration in the cost of a potential fuel cycling facility in which used CANDU fuel is used to replenish the heavy atom requirements of used FNR fuel.

7. A Hypothetical Fuel Cycle Facility For A Fast-Neutron Reactor

In order to obtain a quantitative understanding of the used fuel processing capacity requirements for starting and running an FNR, a potential real reactor facility must be considered. The example described here includes the 300 MWe design of the PRISM FNR by GE-Hitachi in the USA [14]

In round numbers that reactor requires about 22.5 tons heavy atoms of which 2.1 tons are TRUs with about the same fissile content as the TRUs in used CANDU fuel. The fuel dwell time is 5.75 years. One third of the load is replaced every 2 years. The remaining fuel assemblies are shuffled within the core.

7.1 Reactor Start

To start such a reactor would require the 2.13 ton TRU fuel load plus another one third, or 0.71 tons TRUs for the first one third replacement of fuel after 2 years.

This 2.84 ton TRU supply could be obtained from 750 tons used CANDU fuel which has a TRU content of 0.38% [7, p.341].

If we assume a capacity for used CANDU fuel pre-treatment crystallization of 100 tons/year, a five year operation would furnish TRUs sufficient to load one FNR reactor core equivalent to the 300 MWe PRISM, while a further two years would yield the required TRUs for the first fuel shuffle/replacement operation. The crystallization would leave behind a heavy atom fraction of 10 tons/year with a mix of uranium, all of the TRUs needed and all of the fission products.

Therefore an associated pyroprocessing facility with a capacity of only 10 tons/year would be large enough to separate out the FPs and some of the uranium to furnish the fuel at the right uranium/TRU composition for FNR operation.

In the process the 90% pure depleted uranium, or 675 tons, from uranium crystallization are set aside for future use as fuel in an FNR, as are a further 50 tons from pyroprocessing, for a total 725 tons depleted uranium. Furthermore, 5.6 tons fission products (0.74% of 750 tons used CANDU fuel "waste") would be separated and require safe storage.

7.2 Normal Reactor Operation with Used CANDU Fuel Replenishment

Once normal operation of this FNR has begun, about one third of the fuel, 7.8 tons, is removed every two years for processing. About 15% of this fuel, or 1.17 tons, would have been converted to fission products in those two years and would need to be separated from the used FNR fuel by pyroprocessing. This would require a facility with a capacity of 3.9 tons of used fuel per year to service the 7.8 tons.

Pyroprocessing would separate 0.58 tons/year fission products and also extract close to 60% of the uranium from the fuel, or 2.34 tons/year. The sum, 2.9 ton/year FNR fuel could be replaced with the 10% TRU-containing fraction from the crystallization pre-treatment of used CANDU fuel (above), requiring the crystallization treatment of 29 tons/year of used CANDU fuel. The 0.21 tons FPs, carried with this fuel fraction, would be separated by pyroprocessing in the next FNR fuel cycle. At the same time, while the used CANDU fuel lasts, 28.4 tons/year of depleted uranium would be set aside and stored as future FNR fuel, 26.1 tons from uranium crystallization and 2.3 tons from pyroprocessing.

7.3 Operation with Depleted Uranium Replenishment

Once no further used CANDU fuel is available, FNR fuel replenishment can be accomplished with the stored depleted uranium. The electrolytic separation of FPs by pyroprocessing still requires a capacity of 3.75 tons/year for each 300 MWe reactor, extracting about 0.5 tons/year of FPs. Only the corresponding 0.5 ton deficit of heavy atoms in the fuel has to be replenished, and can be done using 0.5 tons/year per reactor from the stored depleted uranium.

8. Speed of Reduction and Elimination of TRU-containing Used Fuel

The numbers in Section 6 and 7 permit an estimate of the speed with which currently stored used CANDU fuel could be processed to extract and use its long-term radiotoxic TRUs. When the Pickering nuclear station is shut down as planned in 2020, about 15,000 tons of used CANDU fuel will be on site. This scenario can serve as an instructive hypothetical example of used fuel management via a combination of on-site fuel cycling facilities coupled to TRU-burning FNRs. Such an approach would avoid the need to transport highly radioactive used fuel to other locations, and at the same time maintain and stimulate the economy of the region.

Table 1 provides data for one 300 MWe reactor, as well as for 5 and 10, the latter having a combined output of 3000 MWe equal to the approximate total power output of the current Pickering reactors.

The remarkable result is the realization that the TRUs with their long-lived radiotoxicity in the 15,000 tons used CANDU fuel would be extracted and used up in as few as 26 years with FNRs equal in power to the current Pickering reactors. Remaining would be 14,593 tons of rather benign depleted uranium as future fuel. In addition, the 15,000 tons of used fuel would yield 111 tons of fission products, with a continuing additional annual trickle of about 0.5 tons FPs per 300 MWe reactor as the depleted uranium is gradually used up over almost 3000 years.

Table 1. Representative Scenarios of Used CANDU Fuel Reuse in a Fuel-Cycle/Fast-Neutron Reactor Facility.

Reactors	Power Output	Start-up with used CANDU fuel	Used CANDU Fuel remaining	Required Used CANDU fuel for operation	Time to Used CANDU fuel depletion	Build-up of depleted uranium	Depleted uranium fuel resource at 0.53 t per reactor-year
#	(MWe)	(tons)	(tons)	(tons/yr)	(years)	(tons)	(years)
0			15,000 (expected in 2020)				
1	300	750	14,250	29	491	14,680	27,910
5	1500	3750	11,250	145	78	14,641	5,567
10	3000	7500	7,500	290	26	14,593	2,775

9. Fission Product Lifetimes

Fission products (FPs) extracted from the used CANDU fuel, as well as new fission products produced in the operation of the FNRs, to be safely sequestered. Figure 1 suggests that safe storage for about 300 years may be all that is needed, something well within the near-history of mankind. Cycling over 300 years of initially highly radioactive FP elements through a suitably shielded storage provision would result in virtually all FPs emerging as potentially useful and valuable non-radioactive metals and minerals at the end of such storage.

The evolution of heat during the decay of the FPs is a concern for such storage. However, it is known that much of this heat generation declines after 30 years, suggesting that after that time a safe storage facility might become relatively compact.

Figure 1 indicates that some fission products have fairly long half-lives, close to a million years or longer, and may cause some unease even though their radiotoxicity is well below the level of uranium from which they were created in the reactor. Table 2 shows some of these long-lived fission products. Iodine-129 (I-129), though at radiotoxicity levels 37,300-fold less than uranium, is frequently singled out as being of concern in DGRs should containment be breached. However, I-129 may be a particular non-problem in the context of a fuel-cycle/FNR facility as outlined below.

The discussion in Sections 4 and 6 above indicated that two procedural stages of processing incorporate fairly high temperatures (500ºC and 600ºC). In pre-treatment of used CANDU fuel as well as in pyroprocessing iodine with a boiling point of 184ºC would be vaporized, then captured and condensed. Iodine of any reasonable age has only two isotopes, stable iodine-127 and long-lived iodine-129 with a

Table 2. Long-lived Fission Products: Transmutation Potential

Isotope	Radiotoxicity Relative to Uranium	Half-life (M years)	Thermal Rad. Capt. Cross Sec. (barns)	Product	Decay Time	Product	
Tc-99	1/35	0.211	22	Tc-100	17 s	**Ru-100**	**stable**
Cs-135	1/510	2.3	8.7	Cs-136	13 d	**Ba-136**	**stable**
Zr-93	1/800	1.5	4	**Zr-94**	**stable**		
Se-79	1/10020	0.295	50	**Se-80**	**stable**		
Sn-126	1/10020	0.23	0.09	Sn-127	2.5 h > 93 h > 9.4 h > **I-127 stable**		
I-129	1/37300	16	30	I-130	12 h	**Xe-130**	**stable**
Pd-107	1/336700	6.6	2.1	**Pd-108**	**stable**		
I-127	**stable**		6.2	I-128	25 m	**Xe-128**	**stable**

half-life of 16 million years. Even without separation of the isotopes the iodines can be inserted into a thermal reactor for transmution to iodine-128 and iodine-130 respectively (Table 2). Both of these have short half-lives, 25 minutes and 12 hours, respectively, and decay into stable isotopes of xenon. Even if those xenon isotopes absorbs neutrons, the result is a long series of stable heavier xenon isotopes.

Thus iodine can be readily converted from a 16-million-year radioactivity concern into a stable element. Suitably isolated, the small number of other long-lived FP isotopes might be similarly transmuted.

10. Deep Geological Repository or Storage

The potential of energy extraction from used CANDU fuel while at the same time neutralizing its long-term radiotoxicity suggests that the concept of a deep geological repository for such fuel should be re-examined. Without the need to sequester the long-lived TRUs the need would be for a retrievable shielded storage facility for FPs, of which only about 30% are radioactive. Most of those would lose their radioactivity and heat-generating capacity in a few decades, with the possibility of a substantial reduction in required storage volume. Only two FPs, Sr-90 and Cs-135, require 300 years. A few very-long-lived FPs would require special attention and be extracted and treated at the outset, e.g. iodine as shown above, or perhaps at the 300-year time point. At that time many of the valuable FPs, such as rhodium, ruthenium, or the rare earths, could be extracted by normal procedures. It has been estimated that altogether the FPs, when non-radioactive, would fetch about $2.5 million per ton at today's prices.

10. Conclusion

The introduction of a fuel-cycle/fast-neutron reactor mix into Ontario's fleet of CANDU reactors to re-use existing and future used CANDU fuel "waste", turning it into energy, would change the complexion of the nuclear industry. The legacy of long-term million-year radiotoxicity of transuranic actinides would be eliminated, and the used fuel would be turned into a non-carbon energy resource

that could power Ontario for several thousand years at current levels of nuclear power production. It would, with a very positive solution, remove one of the major objections of the populace to the acceptance and growth of the whole nuclear industry.

The pieces of the technology exist and have been demonstrated and tested. They merely have to be put together in Ontario.

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