# Canada's Used Nuclear Fuel Waste: A 20 Trillion Dollar Energy Resource Energy Extraction and Partial Detoxification in Fast-Neutron Reactors

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## Abstract

Canada's 40,000 tonnes of used nuclear fuel waste are slated to be interred in the Canadian Shield at a cost of $24 billion. This "waste" consists of 0.74% fission products and 99.26% actinides, with 98.81% uranium and 0.45% long-lived transuranic actinides. All these actinides can fuel fast-neutron reactors, leaving only 70% stable and 30% short-lived fission products. Calculations here show that the nuclear energy reaped in the process can create $20 trillion of electricity. Additionally, the tonnes of elements such as rhodium, palladium, ruthenium and technetium in the resulting fission products would be worth over $150 billion.

## 1. Introduction

General acceptance of nuclear energy by the public is hampered by several concerns, among which the perceived long-term danger of nuclear waste is frequently foremost, followed by concern with nuclear accidents, the risk of the proliferation of nuclear weapons, the apparently limited supply of uranium, and finally the up-front cost of construction. All of these concerns must be continuously and consistently addressed.

This paper is too short to cover all of these concerns, and others, and will concentrate on the use of fast-neutron reactors to provide a different potential approach to eliminating nuclear waste while extracting 135 times more energy from the used fuel. This approach simultaneously addresses the supply of nuclear fuel in general. Nevertheless, it should be pointed out that the safety of North American power reactors, including Canada's CANDUs, is exemplary, with no fatalities nor significant or dangerous spills of radioactivity into the environment, even with the Three-Mile-Island incident, since the inauguration of nuclear-generated electricity production beginning with the EBR-I reactor on December 20, 1951 at 1:50 pm in Idaho [2].

What is generally not appreciated beyond the circle of nuclear experts is that the massive nuclear energy that has been and is being generated in all thermal (slow-neutron) reactors comes via the burning of only part of the 0.72% of uranium-235 (U-235) isotope in mined uranium, and that, even before this component is completely used, the reaction slows and the used fuel has to be replaced with a fresh charge. Only a minimal amount of the 99.28% uranium-238 (U-238) isotope in the fuel is internally converted to plutonium, which, when fissioned, provides about 50% of the energy delivered by the reactor. A further 10% of the energy is derived by fast-neutron fission of U-238 [3]. In total only 0.74% of the incoming uranium fuel provides the prodigious energy that creates about $14 billion of electricity annually from Canada's heavy-water CANDU reactors [5].

Many other countries use light-water reactors, which require enrichment of uranium to increase the neutron-providing U-235 content, since hydrogen, in contrast to deuterium in heavy waster, absorbs more of the neutrons needed to maintain the nuclear fission chain reaction. These reactors burn a greater percentage of their input fuel; but when the depleted uranium left from the enrichment process is counted, even these reactors use less than 1% of the mined uranium.

All slow-neutron reactors therefore leave us with used fuel which is primarily uranium, suffused, in the case of the CANDUs, with 0.74% stable plus relatively short-lived fission products, atoms roughly half the size of uranium, and with 0.45% transuranic actinides, atoms heavier than uranium, including plutonium. The atoms in this latter group have long half-lives, of many thousand years, and so emit dangerous radioactivity far into the future. They constitute the greatest concern of the legacy of used nuclear fuel waste.

The low concentration of the fission products and transuranic actinides make it chemically and physically very difficult to separate the 99% uranium economically from the mix of elements in the used fuel. Therefore some means of safe disposal has been the concern of all countries with nuclear power reactors. Potential burial in deep geological repositories is the virtually uniform train of thought worldwide, although no such repository has been completed to receive used nuclear fuel waste to date.

In Canada studies ranging from the Hare Report in 1977 [4] to the report of the current Nuclear Waste Management Organization (NWMO) in 2005 [5], considered disposal in deep geological repositories in Canadian Shield granite, or in Ordovician layers, between 500 m and 1000 m below ground. The cost of such a long-term repository, containment of used nuclear fuel, deposition and closure is estimated to be as much as $24 billion [5, p.252].

## 2. Slow-Neutron Fission Limitations

More than 99% of the used fuel is uranium and other actinides. Thus it seems logical to ask why not more of this material is fissioned to create energy in current nuclear power reactors. The answers are in the physics of the interaction of neutrons with nuclei and the chosen design of the reactors, plus historical momentum. Slow neutrons very efficiently enter a select type of nuclei, such as those of uranium-235 (U-235) and plutonium-239 (Pu-239) to cause these nuclei to fission and give up their energy and to emit several fast neutrons needed to continue the chain reaction “burning” process. Thus most reactors are designed with light or heavy water surrounding the fuel rods in order to provide a very effective means to slow down the new fast neutrons via collisions with hydrogen or deuterium nuclei of the water molecules. However, slow neutrons do not fission the nuclei of the 99.28% U-238, the major constituent of natural uranium, leaving this potential source of energy untouched. Neither do they fission other transuranic actinides, particularly those with even mass numbers such as Pu-240 or Pu-242, that are created in the reactor stepwise by neutron absorption starting with U-238.

The chain reaction in slow-neutron reactors slows even before the 0.72% U-235 is used up, because some of the medium-sized atoms that are created as fission products when uranium or plutonium nuclei are split absorb slow neutrons very strongly. While the neutron cross-sections of U-235 and Pu-239 for the fission process are 580 barns and 760 barns respectively, the absorption cross-section of fission products xenon-135 (Xe-135), gadolinium-157 (Gd-157) and samarium-149 (Sm-149) are 2,640,000 barns, 254,000 barns and 41,000 barns respectively (see Table 2, below). Thus as fission proceeds, the build-up of even very small percentages of these fission product isotopes slows and eventually stops the reaction. In the CANDU reactors this occurs when about one third of the available U-235 is still unused. At this point the fuel is withdrawn from the reactor and replaced with fresh natural uranium. The used fuel becomes “waste”, since reprocessing to extract and remove such a small total percentage of the neutron-absorbing fission products is currently uneconomical.

Nevertheless, the yield of nuclear energy from even the small percentage of U-235 and from the Pu-239 created in every reactor is so huge that greater use of the uranium fuel for power production was not considered sufficiently important. Quite reasonably, larger reactors, ever-greater safety in design, and more efficient transfer and use of the thermal energy to create electricity were greater concerns of reactor manufacturers. Uranium fuel has been a relatively minor proportion of the financial investment needed for the building and running of a nuclear reactor. Moreover, the disposal of nuclear waste was relegated by law to be the responsibility of federal governments rather than that of the operators of reactors [6].

The current climate is forcing a reassessment of the worldwide energy scenario in the nuclear field. The continuing use, perforce, of only 1% of mined uranium in slow-neutron power reactors has led to calculations that relatively inexpensive uranium reserves, at less than $120 per kilogram, will be exhausted within about 100 years at current usage [7]. And separately but relatedly, the disposal of the accumulating high-level used nuclear fuel waste is still a very sensitive unresolved issue.

Both issues can be resolved simultaneously by nuclear physics, using fast-neutron reactors.

## 3. Fast Fission

In CANDU reactors about 10% of the energy is obtained via fast-fission reactions. In this process some of the fast neutrons that are created in the splitting of an atom in the fuel rod find a U-238 atom, likely in the same fuel rod, and split it before they exit the rod and are slowed down by the moderating surrounding water. A few neutrons, of intermediate energies, are resonantly captured by U-238 nuclei and cause the transmutation of U-238 to U-239, Np-239 and finally to Pu-239, the latter being an excellent target for slow-neutron fission.

Thus a small proportion of the 99.28% U-238 atoms are used in energy production. This portion is difficult to increase in the presence of so much surrounding water that slows down neutrons. However, elimination of the water as a moderator provides a different scenario, since neutrons now retain their speed much longer. As a result fast neutrons can find U-238 in neighbouring fuel rods without meeting water to slow them.

However, to increase the probability of neutron interaction with the fuel a medium must be provided to scatter them elastically before they escape to the walls of the reactor core. To decrease the chance of neutron loss further, the medium should absorb neutrons minimally. In addition, the medium has to carry away the heat created by the fast-fission process to cool the reactor and to transfer the energy out of the reactor for use elsewhere. While gases, such as helium at high pressure, have been used [8], liquids are denser, and so can scatter neutrons elastically more strongly without the need of pressurization.

Liquid media that have been used in fast-neutron reactors are sodium, lead, or a eutectic alloy of lead and bismuth [8]. For comparison, some of the physical properties of a number of potentially suitable low-melting elements and alloys are indicated in Table 1, along with "figures of merit" that combine positive and negative characteristics. It is clear that from

| A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|
| | **Melting** | **Boiling** | **Neutron Cross-Sections*** | | | **Figures of Merit** | | |
| **Elements** | **Temp. °C** | **Temp. °C** | **Elastic (barns)** | **Absorpt'n (barns)** | **Density g / cc** | **D / E** | **D / E relative to Na** | **H / G relative to Na** |
| **Na (as reference)** | **97.8** | **892** | **1.4** | **0.0040** | **0.97** | **350** | **1.00** | **1.00** |
| Cs | 28.4 | 678 | 4.6 | 0.0290 | 1.88 | 159 | 0.45 | 0.23 |
| Ga | 29.7 | 2237 | 3.0 | 0.1500 | 6.10 | 20 | 0.06 | 0.01 |
| **K** | **63.7** | **774** | **2.9** | **0.0003** | **0.86** | **9667** | **27.62** | **31.15** |
| In | 156.2 | 2000 | 5.8 | 0.2300 | 7.30 | 25 | 0.07 | 0.01 |
| Sn | 231.9 | 2270 | 4.7 | 0.5000 | 6.50 | 9 | 0.03 | 0.004 |
| **Bi** | **271.3** | **1560** | **5.0** | **0.0020** | **9.80** | **2500** | **7.14** | **0.71** |
| Cd | 320.9 | 765 | 4.0 | 0.0300 | 8.64 | 133 | 0.38 | 0.04 |
| **Pb** | **325.6** | **1725** | **4.7** | **0.0026** | **11.30** | **1808** | **5.17** | **0.44** |
| Sb | 630.5 | 1300 | 6.4 | 0.0270 | 6.68 | 237 | 0.68 | 0.10 |
| **Low-Melting Alloys** | | | | | | | | |
| Bi(44.7),Pb(22.9),Sn(8.3),Cd(5.3),In(19.1) | 46.8 | 765 | 5.0 | 0.0885 | 9.36 | 57 | 0.16 | 0.02 |
| Bi(49),Pb18, Sn(12), In(21) | 58.0 | 1560 | 5.1 | 0.1100 | 9.15 | 46 | 0.13 | 0.01 |
| Bi(50),Pb(26.7),Sn(13.3),Cd(10) | 70.0 | 765 | 4.8 | 0.0712 | 9.65 | 67 | 0.19 | 0.02 |
| **Bi(52),Pb(40),Cd(8)** | **91.5** | **765** | **4.8** | **0.0045** | **10.31** | **1071** | **3.06** | **0.29** |
| Bi(52.5),Pb(32),Sn(15.5) | 95.0 | 1560 | 4.9 | 0.0794 | 9.77 | 61 | 0.17 | 0.02 |
| Bi(50),Pb(31.2),Sn(18.8) | 97.0 | 1560 | 4.8 | 0.0950 | 9.65 | 51 | 0.14 | 0.01 |
| **Bi(55.5),Pb(44.5)** | **124.0** | **1560** | **4.9** | **0.0023** | **10.47** | **2150** | **6.14** | **0.57** |

* From Brookhaven National Laboratory ENDF files [9]; other data from [10]

Table 1 Characteristics of low-melting-point elements and alloys

a physics point of view potassium is the best liquid medium with the highest figure of merit in terms of minimal neutron absorption, sufficiently large elastic scatter cross-section and low density. However, its very strong chemical reactivity argues against its use. Sodium is chemically less reactive and is used in most fast-neutron reactors to date, even though it has a ten-fold higher neutron absorption than potassium. An argon blanket cover on the surface of the liquid sodium protects it from reacting with its surroundings.

In terms of elastic scattering and neutron absorption lead and bismuth are better than sodium, but have much higher melting temperatures. However, a eutectic alloy of these two metals, somewhat similar in physical and chemical characteristics to ordinary solder, has a melting point of 124ºC, only slightly higher than sodium at 98ºC. This eutectic composition has been used in some Russian fast-neutron reactors [8].

Heat transfer characteristics are important for power reactors. Thermal conductivity is not a major consideration, since all metals have better heat conductivity than the light or heavy water used in current thermal slow-neutron power reactors [10]. Virtually all materials have the same heat capacity per mole, meaning that a lighter material such as sodium has a greater heat capacity per kilogram than lead or lead alloys [10]. This factor is taken into consideration in the figure of merit in column "I" of Table 1. Again, potassium is far superior to sodium. Bismuth is 70% as good as sodium and the 55.5/45.5 bismuth/lead eutectic alloy is close to 60%. For the latter it may be useful to use the eutectic in the core of the reactor and a separate loop in and out of the core with a lighter heat-transfer medium for energy transfer.

Fast-neutron reactors have been built since the 1950's, with the sodium-cooled U.S. EBR-I with a core size only slightly larger than a five-gallon drum of roofing tar (Fig. 1) taking the

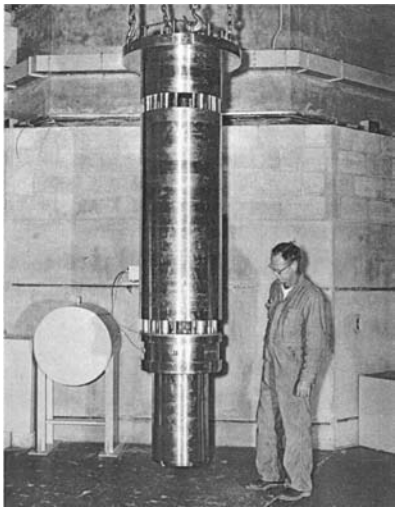


Figure 1 Photograph of the core assembly of the sodium-cooled EBR-I fast-neutron reactor during construction (from [2])

honour of producing the first electricity from nuclear energy, initially to four light bulbs. Its bigger brother, the EBR-II produced 20 MWe of power and ran successfully and without incident from 1964 to it decommissioning in 1994. It was also used as a test bench to simulate the events leading to the Three-Mile-Island TMI-2 incident [1] as well as the Chernobyl-4 (RBMK) disaster [13]. The reactor, built with natural passive safety features, shut itself down in each case [12]. A still larger version, the French Phenix sodium-cooled reactor produced 233 MWe of electricity as part of its research program until 2009 [14].

All fast-neutron reactors in the western world were sodium-cooled research reactors. Only the Russian sodium-cooled BN-350 and BN-600 reactors were and are sodium-cooled commercial power reactors producing heat for desalination of seawater and for electricity in the 350 to 600 MWe range, respectively [15]. Russia also built lead-bismuth-cooled smaller fast-neutron reactors for its submarine fleet [16], while currently it has orders for two sodium-cooled BN-800 fast-neutron reactors from China and is building one for itself.

Two other nations, India and Japan, have several smaller sodium-cooled fast reactors.

## 4. Fuel Burn-up in Fast-Reactors

Fast-neutron reactors were not designed directly for "burning" used nuclear fuel waste, since this was not at all considered a priority. In the decades of the east-west arms race it was found that these reactors could be designed to convert uranium efficiently to plutonium, which could be used in the manufacture of bombs, but also provide fuel for conventional water-moderated power reactors. The fast-neutron reactors are often referred to as "fast breeder" reactors, with a corollary statement that they "breed" more fuel than they burn. While plutonium is produced by conversion from uranium, as it is in every nuclear reactor, uranium fuel and some of the plutonium is used up in the process, i.e. there is less total fuel at the end rather than more. Indeed, fast-neutron reactors have been designed which are mundanely labelled "break-even reactors" [17], in which the plutonium is used up as fast as it is produced from U-238.

### 4.1 Increasing the burn-up

In the earliest fast-neutron reactors such as the EBR-I it was found that fuel had to be replaced after virtually the same 1% to 3% burn-up as in water-moderated reactors using enriched uranium. The fuel containers would rupture at those levels from physical swelling of the fuel and from chemical interaction with the cladding of the container [18].

This problem was alleviated by not filling the container completely, by instituting a "smeared density" of 75% to 85%. This meant that on average the cross-section of the fuel rod was only 75% to 85% of the inner cross-section of the container. This decreased the direct chemical contact and direct physical pressure between the expanding fuel charge and the cladding, the wall of the container. At the same time the container metal was changed from 304 and 316 stainless steels to austenitic D9 and then to a stronger martensitic HT9 steel. The result was an increase in burn-up to a safe 8% before the "fuel pin", the fuel and its container, had to be exchanged. When burn-up was tested deliberately beyond the safe 8% level, breaching of the fuel container was observed at around 10.5% burn-up. From metallurgical failure analysis it was determined that rupture occurred from an internal pressure build-up from gaseous fission products, with the fuel container bursting in the upper, hotter part of the reactor core [18].

Analysis of the reacted fuel itself indicated that gaseous fission products, such as xenon, krypton, and iodine vapour at high reactor temperatures, would initially form non-contiguous voids or cavities in the fuel, causing it to swell. This was the prime reason for fuel/cladding contact when "smeared density" values were initially close to 100%. After 2% burn-up the voids in the fuel would start to coalesce into a contiguous network open at the surface of the fuel, permitting release of the gaseous products directly into the closed fuel canister. Thus one could consider the structure of the fuel to proceed from the equivalent of an expanding closed-cell foam to a virtually constant volume open-cell foam at around 2% burn-up and beyond.

As burn-up increased more gaseous fission products formed, and the pressure in the closed container built up until it was high enough to burst the canister. This realization brought about a second change in fuel container design: the addition of an extra volume, or plenum, of empty space equal to 60% of the fuel volume. This simple modification that was instituted in

the EBR-II brought the safe burn-up limit to about 18%. Tests indicated that fuel-container rupture would now not occur until a burn-up of around 23% was reached. With this design well over 30,000 fuel pins were safely reacted in the EBR-II core up to the 18% burn-up levels in the 30 years of operation of this reactor [18]. A higher burn-up was not sought, since at 18% burn-up the energy extraction from uranium was already over one order of magnitude higher than the yield in water-moderated reactors.

After the EBR-II was decommissioned several commercial designs were created by G.E. based on the experience with this reactor. Of these the 1997 ALMR (Advanced Liquid Metal Reactor) [17] and the more recent sPRISM [19] are examples that would emulate the 18% burn-up capabilities of the EBR-II. None have been built, as water moderated reactors even at a 1% uranium burn-up have continued to produce prodigious amounts of energy.

However, research efforts have continued with attempts to determine the burn-up potential of used nuclear reactor fuel waste. Thus fuel pins were constructed with mixtures of uranium, transuranic actinides and “fissium”, a mixture of a number of fission product elements, to be “burned” to the 25% level in the French Phenix reactor. Both metal fuels and metal-oxide fuels were tested. To reach the 25% burn-up level safely, the plenum, or empty volume in the fuel pin was increased to two times the volume of the fuel charge [20].

## 4.2 Idealized burn-up levels

What becomes obvious in the discussion above of moderate burn-up levels in fast-neutron reactors is that greater fuel usage was limited primarily by the design of the fuel container. In contrast, the neutron-requiring chain reaction in slow-neutron reactors ceased when a build-up of even small percentages of fission products absorbed too many of the slow neutrons. This difference in reactivity is understandable from the difference in the neutron absorption cross-sections of some of the predominant fission products. Table 2 compares the thermal and fast-

| Fission Product | Yield<br>% | Thermal Absorption Cross-Section<br>(barns) | Weighted Therm. Absorp. Cross-Section<br>(barns) | Fast-Neutron Absorption Cross-Section<br>(barns) | Weighted Fast Absorption Cross-Section<br>(barns) |
|---|---|---|---|---|---|
| Xenon-135 | 6.33 | 2,640,000 | 167,000. | 0.010 | 0.00063 |
| Samarium-149 | 1.09 | 41,000 | 446. | 0.20 | 0.0022 |
| Samarium-151 | 0.42 | 15,000 | 63.1 | 0.092 | 0.00039 |
| Gadolinium-157 | 0.0065 | 254,000 | 16.5 | 0.088 | 0.0000057 |
| Europium-155 | 0.033 | 14,000 | 4.6 | 0.11 | 0.000036 |
| Promethium-147 | 2.27 | 95 | 2.2 | 0.19 | 0.0043 |
| Cesium-134 | 6.79 | 29 | 2.0 | 0.044 | 0.0030 |
| Technetium-99 | 6.05 | 22 | 1.3 | 0.0072 | 0.00044 |
| Total | 16.7 | | 167,727.1 | | 0.011 |

Table 2. Comparison of thermal and fast-neutron (1 MeV) absorption cross-sections for the top eight absorbing fission product isotopes in thermal slow-neutron reactors [8,9]

neutron cross-sections of the top eight absorbers of thermal neutrons among the fission products. Almost uniquely, Xe-135 stands out as the prime isotope that slows and stops the thermal fission reaction. It is one of the major fission products and has an absorption cross-section of 2.64 million barns. In contrast its fast neutron cross-section is only 0.01 barns [9]. Considering the concentration-weighted contributions of all fission product absorption cross-sections, Xe-135 accounts for about 99.6% of thermal neutron loss from all fission products.

Whereas the twenty strongest absorber fission products for slow neutrons have a total weighted cross-section of 167,700 barns, with Xe-135 contributing 167,200 barns alone, the total weighted cross-section of those twenty fission products for fast neutrons is only 0.014 barns, with Xe-135 contributing a mere 0.00063 weighted barns. Thus the number of fast neutrons in fast-neutron reactors is reduced only minimally by fission products at low and intermediate burn-up levels.

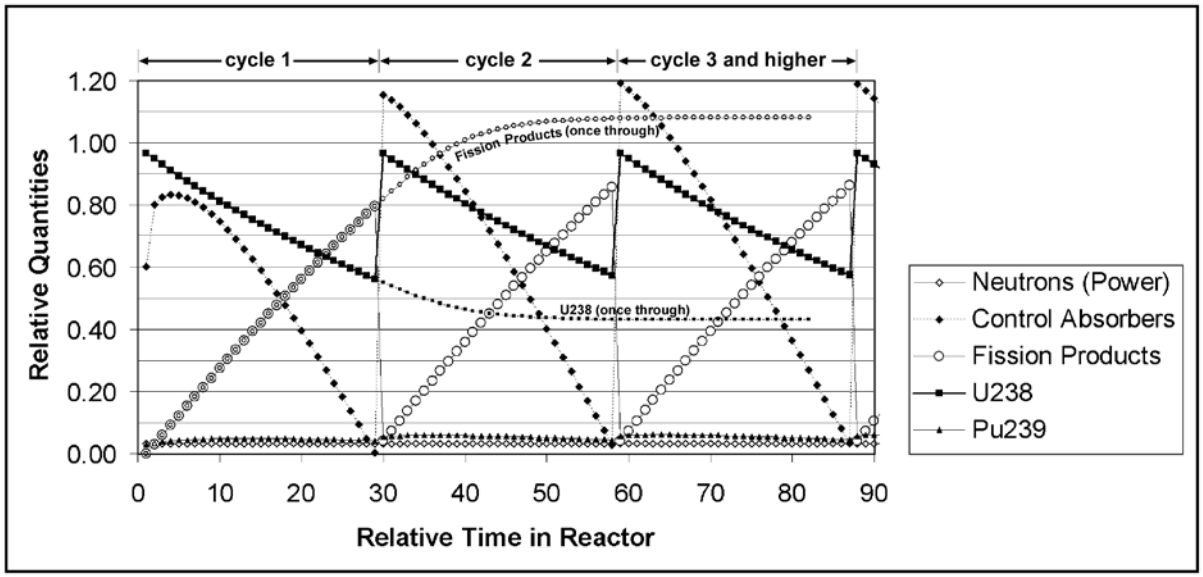
If the limitations for a burn-up as high as 25% are set by the design of the fuel container in fast-neutron reactors, how high a burn-up could be achieved if an idealized container were built? In such a fuel container there would be no direct pressure of the expanding fissioning fuel on the walls of the canister (sufficiently small “smeared density”) and no build-up of internal pressure from gaseous fission products (“open” container).

Figure 2 shows an example of the results of approximate calculations for such an idealized case in a fast-neutron reactor using a liquid metal eutectic alloy of 55.5/44.5 bismuth/lead as scattering medium and coolant in the reactor core (when sodium properties were used in the calculations the differences were minimal). Each cycle of calculations apportioned an incoming number of neutrons from the previous cycle according to the relative cross-sections for fission, transmutation and/or absorption, elastic and inelastic cross-sections of constituent atoms in the fuel rod, a proportionate number for control rod absorptions, for losses in the heat exchange medium in the core and for losses in the reactor structural components. Three contiguous energy regimes were considered: from 2 MeV to 1 MeV, 1 MeV to 10,000 eV, and 10,000 eV to 0.1 eV. Only a negligible number of neutrons scattered into the lower-energy thermal regime below 0.1 eV. Within each of the three regions, cross-sections from numerical listings available from ENDF files [9] were averaged logarithmically to parallel the constant fraction of energy loss per elastic neutron interaction. Neutrons gained from the resulting fission events were then used as input for the next mathematical cycle.

## 5. Application of Fast-Neutron Fission for Used Nuclear Fuel Waste Elimination

The calculations for Fig. 2 considered the composition of elements corresponding to used nuclear fuel from CANDU reactors [5, p. 341], as well as the relative volumes of fuel, coolant and structural materials from the sPRISM reactor design [19]. Only levels of U238, Pu239, fission products and control absorbers are shown for clarity, although calculations included higher actinides as well as U235 and U236. To start the “reactor” calculations at a reasonable power level the used fuel was “enriched” to 3 wt% Pu239/HM. The calculations indicate that for a “once-through” scenario fuel burn-up should proceed to about 56% before the chain

reaction would be stopped due to loss of fast neutrons from fission products (Fig. 2). If a constant power level is to be maintained indefinitely, then used fuel has to be removed after a burn-up level of about 41% and the built-up fission products separated by such methods as pyroprocessing [11]. The fuel charge is then topped up with currently stored used uranium from CANDU reactors. No further Pu239 need be added to maintain the chain reaction, since




the Pu239 levels increase in the reactor to about 6% near the beginning of each cycle from

Figure 2 Approximate calculation of behaviour of used nuclear fuel "waste" from CANDU reactor in fast-neutron reactor with liquid Bi/Pb coolant in core. Three cycles of fuel top-up are shown

conversion of U238 to Pu239 and then drop only to about 4.5% at the end of the cycle. Control rod absorptions maintain the power level as the two isotopes of uranium and any transuranic actininides are fissioned or transmuted into further transuranic elements that then in turn are fissioned or transmuted. Several cycles are shown in Fig. 2. At the end of each cycle the level of transuranic actinides is constant, indicating that all of the uranium and long-lived transuranic waste elements in the top-up charge of used fuel are completely "burned".

The interesting observation of the use and destruction of CANDU used fuel waste is the creation usable energy. In burning this used fuel, about 135 times more nuclear energy would be extracted from the fuel than was gained already by the 0.74% burn-up during prior use in the heavy water reactor. At the same time the high-level nuclear reactor fuel waste would be purged of long-lived transuranic isotopes. What is left at the end are only fission products 70% of which are non-radioactive. The remaining 30% decay with half-lives about 400 times shorter than the transuranic actinides (cf. Fig. 3a and Fig. 3b), except for a few weak beta-emitters such as Tc-99, shown in Fig. 3, and minor components such as Zr-83.

This behaviour is illustrated in Fig. 3 for two different time spans. At early times, after a number of years of the usual cooling period in pools and a number of decades in dry storage, the current CANDU used fuel would have reached a level where the transuranic actinides

remain about 1000 times more radioactive than native uranium for thousands of years (Fig. 3a). This component would be eliminated with the use of fast-neutron reactors in the process of energy extraction.

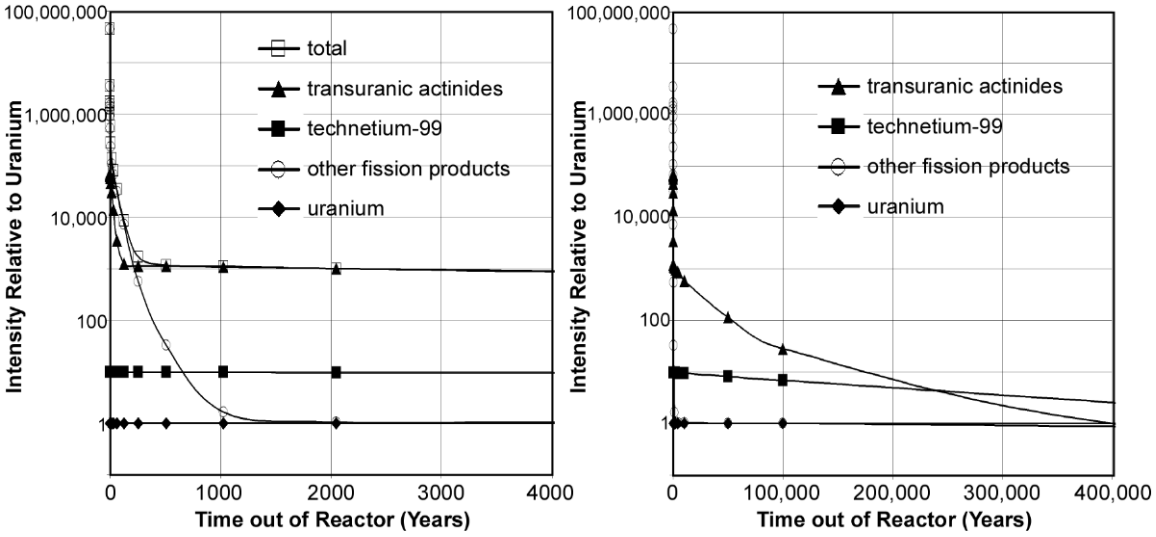



Figure 3 Two time spans, 0 to 4000 years (a), and 0 to 400,000 years (b), showing the radioactive emissions in CANDU used fuel relative to uranium, for major transuranic actinides, Tc-99 as a long-lived isotope product and for other fission products

The shorter-lived fission products continue to decay relatively rapidly (Fig. 3a). At long times, of the order of 400,000 years, the major transuranic actinides would have decayed as well in current used fuel "waste" (Fig. 3b) while a small percentage of very long-lived fission products would remain. One might consider disposal of the fission products after they are separated from the energetically spent fuel from fast-neutron reactors. However, a consideration of the value of the non-radioactive components among the fission products may first spawn a different initial action.

## 6. Financial Payback

### 6.1 Stored high-level used nuclear fuel "waste"

The nuclear energy potential in the currently stored 40,300 tonnes of uranium in used fuel uranium oxide "waste" [5] from Canada's nuclear reactors is enormous. It has been estimated that 180 tonnes of uranium fuel currently produce about 1 GW-year of electricity in water-cooled reactors. Since in CANDU reactors only 0.74% of the fuel in this uranium is fissioned, complete uranium burn-up in a fast-neutron reactor would mean 135 times as much energy could be extracted from this used fuel in a fast reactor. This leads to an interesting calculation:

Instead of requiring 180 tonnes of uranium
a fast-neutron reactor would require 1.33 tonnes of U-"waste" for 1GWy of electricity
Canada has 40,300 tonnes of U-"waste

In a fast-neutron reactor
these 40,300 tonnes would produce **30,300 GWy** of electricity

1 GWy = 8,760 million kWh of electricity

= $ 701 million at 8 ¢/kWh to the consumer

Therefore the currently stored 40,300 tonnes of used nuclear fuel "waste"
have a consumer value = **$ 21.2 trillion** of electricity.

### 6.2 Fission products from fast-neutron reactor

On the assumption that the 40,300 tonnes of uranium in Canada's used reactor fuel will be completely fissioned in fast-neutron reactors, with the production of 40,300 tonnes of fission products, it is interesting to contemplate the separation of the multitude of components in this volume of medium-sized atoms.

Among the stable elements in the fission products would be barium (3250 tonnes), bromine (30 tonnes), cadmium (150 tonnes), dysprosium (2 tonnes), molybdenum (4700 tonnes), rhodium (660 tonnes), ruthenium (3060 tonnes), silver (110 tonnes), and terbium (4 tonnes) as estimated from the relative percentages of these elements in the fission products. Among the interesting slightly radioactive elements is technetium (1100 tonnes), a substance that does not occur in nature, and palladium (1900 tonnes), an element in the platinum family.

The value of the stable elements rhodium and ruthenium alone is $58.3 billion and $15.7 billion respectively on today's markets, while the slightly radioactive but not otherwise obtainable technetium is worth $66 billion [21]. These high monetary values might make storage, rather than burial, of eventual fission products a logical choice until safe extraction methods are applied or the total radioactivity has sufficiently decayed.

## 7. Conclusions

Canada's 40,000 tonnes of used nuclear fuel waste, primarily uranium, worth $48 billion at $120/kg, can produce $20 trillion of electricity at 8 ¢/kWh to the consumer, using fast-neutron reactors capable of fissioning all actinides including highly radioactive transuranics in the "waste". At Canada's current annual output of $ 14 billion of nuclear-generated electricity, this source of fuel alone would supply this level of electricity for over 1,500 years, or therefore alternatively easily replace all carbon sources for electricity for many centuries. Such fast-neutron reactors exist, and though not currently designed for high fuel burn-up, have achieved 25% burn-up levels. Such reactors should be built in Canada to make inroads into utilizing and largely detoxifying the current stored used nuclear fuel waste. Future reactors can be designed to achieve higher burn-up levels, over 50% in a single pass, since the limitation to continued fission at present is not in neutron absorption but in the design of reactor fuel containers. In addition to the prodigious amounts of electricity that could be produced, the final fission products from the fast-neutron fission process of Canada's 40,000 tonnes of stored used reactor fuels would contain many tonnes of valuable elements,

including stable elements whose value, when they have been separated, is upwards of $150 billion at current prices, more than the cost of the uranium fuel from which they arose.

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## 9. References

[1] http://www.world-nuclear.org/info/inf36.html
[2] http://www.anl.gov/Media_Center/logos20-1/ebr1.htm
[3] "CANDU Fundamentals". Available at http://canteach.candu.org/library/20040701.pdf
[4] A.M. Aikin, J.M. Harrison, F.K. Hare, "The management of Canada's nuclear wastes", Energy, Mines and Resources Canada, Report EP 77-6, August 31, 1977.
[5] E. Dowdeswell, K. Nash, "Choosing a way forward: the future management of Canada's used nuclear fuel", NWMO, 49 Jackes Ave., Toronto, Ontario, Canada, M4T 1E2… Also available at http://www.nwmo.ca/Default.aspx?DN=1487,20,1,Documents
[6] "Nuclear Fuel Waste Act". Available on-line in [5, p. 330].
[7] http://www.lbst.de/publications/studies__e/2006/EWG-paper_1-06_Uranium-Resources-Nuclear-Energy_03DEC2006.pdf
[8] http://www.eoearth.org/article/Fast_neutron_reactors_(FBR)
[9] "Evaluated Nuclear Data File (ENDF) Evaluation and Plotting", Brookhaven National Laboratory. Available on-line at http://www.nndc.bnl.gov/sigma/tree/index.html
[10] "Handbook of Chemistry and Physics", CRC Press Inc., West Palm Beach, FL 33409, USA
[11] J.J. Laidler, J.E. Battles, W.E. Miller, J.P. Ackerman, E.L. Carls, "Development of pyroprocessing technology", *Prog. Nucl. En.* Vol. 31, 1997, pp.131-140.
[12] D.C. Wade, R.A. Wigeland, D.J. Hill, "The Safety of the IFR", *Prog. Nucl. En.* Vol. 31, 1997, pp. 63-82; J.I. Sackett, "Operating and test experience with the EBR-II, the IFR prototype", *Prog. Nucl. En.* Vol. 31, 1997, pp. 111-129.
[13] http://www.world-nuclear.org/info/chernobyl/inf07.html
[14] http://www.world-nuclear.org/info/inf40.html
[15] http://www.world-nuclear.org/info/default.aspx?id=528&terms=BN-350
[16] http://www.world-nuclear.org/info/inf34.html
[17] E.L. Glueckler, "U.S. Advanced liquid metal reactor (ALMR)", *Prog. Nucl. En.* Vol. 31, 1997, pp. 43-61.
[18] G.L. Hofman, L.C. Walters, T.H. Bauer, "Metallic fast reactor fuels", *Prog. Nucl. En.* Vol. 31, 1997, pp.83-110
[19] http://www.nrc.gov/reactors/advanced/prism.html
[20] S.L. Hayes, D.L. Porter, "SFR Fuel Performance and approach to qualification". Nov. 27-8, 2007. GNEPNRCSeminarSFRFuels.pdf
[21] http://www.taxfreegold.co.uk/rhodiumpricesusdollars.html; http://www.ebullionguide.com/price-chart-ruthenium-last-30-days.aspx; http://www.radiochemistry.org/periodictable/elements/43.htm