Waste Not, Want Not:
Used Nuclear Fuel Waste as Fuel for a Thousand Years

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Abstract

Used nuclear fuel waste is a huge source of non-carbon energy, rather than a liability. Less than 0.75% of the energy content in mined uranium is extracted in thermal reactors before the fuel is considered "waste". All of that energy in used fuel and in depleted uranium can be extracted by fast neutrons. The result is a 100,000-fold reduction in long-term radioactive burden of the "waste", and a $ 36 trillion gain in electrical energy from currently stored used CANDU fuel. Worldwide, fast-neutron reactors could replace all carbon sources of electricity and still provide over 1000 years of electrical energy at current global levels from nuclear fuel waste alone.

1. Introduction

Public acceptance of nuclear power as a reliable and green source of energy is on the rise, reaching 74% in a U.S. survey in June, 2010 [1]. However, some stumbling blocks remain, not the least of which is the ever increasing quantity of long-lived radioactive used nuclear fuel waste that currently requires management for an estimated several hundred thousand years [2]. In Canada this quantity is upwards of 40,000 tons [2], and worldwide it is about 340,000 tons [3].

This particular obstacle to nuclear power can be removed in a very productive way, by converting the used fuel completely to fission products (FPs) while extracting its energy in fast-neutron reactors. The result is not only a 100,000-fold reduction in long-term radioactive burden of the waste, but also the gain of more than 100 times the energy that has already been extracted. The energy from the stored nuclear waste alone and from the associated stored 1,800,000 tons depleted uranium (DU) worldwide would power the World's electricity for 1000 years, and potentially satisfy all energy needs for 340 years. Since virtually no CO_2 is emitted in the extraction of energy from the existing, stored nuclear waste, this source of energy could largely eliminate the man-made CO_2 contribution from greenhouse gases. In addition, the tons of FPs produced, having lost their radioactivity after about 300 years, are a rich source of many valuable minerals, such as rubidium, ruthenium, rhodium and palladium, and many increasingly scarce rare earth elements [4].

The current alternative considered by virtually all nations with nuclear power is to inter the used nuclear fuel in a deep geological repository (DGR), potentially irretrievably. This would be costly. In Canada a DGR, currently planned with the possibility for retrieval for an extended period [5, p8], is expected to cost as much as $ 16 to $ 24 billion [2, p163]. Yet even this price tag for such non-productive nuclear fuel waste disposal is small compared to the energy potential that would be lost should the used fuel become inaccessible by design or by accident. Canada's 45,000 tons of used CANDU fuel could produce close to $ 40 trillion of carbon-free electrical energy and also co-generate heat for industrial and public applications. To forego such an opportunity would be to squander more than $ 1 million in energy for every Canadian.

According to the Nuclear Fuel Waste Act of 2002 [6] it is possible to begin the process of productive elimination of the used fuel waste by consuming it to provide carbon-free energy with funds already designated for nuclear waste management [6, §20(2)]. Only seed funds are needed for an initial nuclear-waste-eliminating fast-neutron reactor facility, since such a facility would be self-supporting, profitable and self-propagating via funds from the sale of electric power and heat created by the reactor.

2. Canada's nuclear waste contribution

Canada's CANDU reactors, although being the most efficient of all thermal reactors in extracting the maximum energy per ton of natural uranium (NU), nevertheless contribute the largest fraction of used fuel waste per ton of mined uranium. CANDU reactors use up only 7.4 grams of fuel per ton NU to extract 5,700 MW-days of energy, and create almost $ 6 million of electricity from the 7.4 g at current household consumer rates [2, p340/351]. The one-ton residue is considered fuel waste.

Light-water reactors (LWRs) require enrichment of fissile uranium-235 (U235) to a level of about 3% U235 or higher [7, p349ff], with the creation of about 5 tons of depleted uranium (DU) per ton of enriched fuel. By converting about 3.4% of heavy metal in the enriched fuel into fission products, LWRs extract 26,000 MW-days of energy per ton of enriched fuel. Only the 1 ton of used LWR fuel is considered high-level radioactive waste; the 5 tons of DU are not.

If one considers energy extracted per ton of mined uranium, then LWR reactors produce only 4,400 MW-days of energy per ton of natural uranium compared to the 5,700 MW-days extracted in CANDU reactors. By this reckoning, CANDU reactors are 30% more efficient than LWRs. However, per unit of energy extracted, CANDUs produce 4 times the volume of used reactor fuel waste of light-water reactors, since DU is not considered to be nuclear fuel waste.

This fact suggests that Canada should take on the responsibility and the lead to create a productive and profitable used fuel waste management regime that not only eliminates used CANDU fuel waste, but that can also be emulated by other nuclear nations. The most productive approach would be to convert the remaining 99.26% heavy metal in the ton of used CANDU fuel also into FPs, to extract a further $ 790 million of electrical energy per ton along with co-generated heat that could be used for industrial and public applications.

Important partial steps in the direction of better utilization of used fuel are explorations to fuel CANDU reactors with used LWR reactor fuel waste [8-12] and to supply these reactors with mixed oxide actinides that contain excess plutonium from decommissioned nuclear weapons [12].

3. Deep geologic repositories for nuclear waste

Currently almost all nuclear nations plan to inter their used fuel waste in deep geologic repositories (DGRs) in whatever local geologic strata are considered most appropriate, e.g. clay (Belgium), salt formations (Germany, U.S.A), granite (Canada, Finland, Sweden, Switzerland), volcanic rock (U.S.A.), or sedimentary layers (Canada) [13].

In Canada major studies have been carried out on nuclear waste disposal, starting formally with the 1977 Hare Report that recommended interment in Canadian Shield granite [14], through the Seaborn Panel [15], the construction of the Underground Research Laboratory in the Lac du Bonnet pluton of the Canadian Shield [16], and culminating with the 2005 Adaptive Phased Management (APM) approach by the Nuclear Waste Management Organization (NWMO) that was created by the 2002 Nuclear Fuel Waste Act [2,6]. The latest recommendation, by the NWMO in the APM, is still for a DGR in Canadian Shield granite or in Ordovician sedimentary rock. Following the dictates of the Nuclear Fuel Waste Act, the NWMO is currently engaged in finding willing communities with appropriate geology in which such a DGR could be sited [5].

A funding mechanism has been instituted to meet the DGR costs estimated to be $ 16 to $ 24 billion by 2035 and beyond [2, p.163]. Funds accrue from the nuclear industries primarily from continuing revenues of nuclear-generated electricity, i.e. paid for by the customer. Current accumulated funds designated for a nuclear waste management facility are upwards of $ 1.8 billion [17,18]. It may be possible to use such funds in a more productive way, below.

4. Change in approach

The Nuclear Fuel Waste Act (NFWA) provides the potential of applying a new approach to nuclear waste management. The NFWA [6] in paragraph 20(2) states:

> *If a new technological method is developed that has been the subject of scientific and technical review by experts from international governmental organizations that deal with nuclear matters and has received their support, the waste management organization may propose, in its triennial report, a new approach for the management of nuclear fuel waste that is based on that new method.*

The NWMO itself commissions reports to keep abreast of technological developments in the field used fuel management [18, p.49]. Thus the foundation exists to change to a more productive direction of used nuclear fuel waste management if it presents itself. The application of a better use of neutrons, particularly fast neutrons, is such a direction. The adoption of such an approach of nuclear waste management would have far-reaching benefits including:

- a 100,000-fold reduction in long-term radioactive burden of the waste
- a true elimination of all plutonium isotopes and other transuranic actinides
- a 130-fold gain in energy yield from the fuel
- a major general reduction in CO_2 from energy production
- the creation of valuable and scarce mid-sized atomic elements
- the creation of more fissile fuel for efficient use in heavy-water CANDU reactors [35]

5. Current fuel utilization

5.1. CANDU fuel

In CANDU reactors the natural uranium with 0.72% fissile U235 is consumed to extract energy with the creation of 0.74 wt% fission products, leaving a combined 0.5% fissile U235, Pu239 and Pu241. At this point the fuel is replaced with fresh natural uranium. Extraction of the 0.5% fissile material is deemed “prohibitively expensive” [18, p49]. The used fuel still contains 99.26% uranium and other heavy atoms that could serve as fuel in fast-neutron reactors.

5.2. LWR fuel

Light-water reactor fuel has to be enriched in fissile element concentration to 3% or more [7, p349ff]. On average, generation II light-water reactors extract energy until a neutron-absorbing FP burden of 3.4% in the fuel is reached. At this point the fissile content is reduced to 1.4%, and the reactor is refueled. The used LWR fuel still contains 96.6% uranium and other heavy atoms.

5.3. DUPIC fuel

Used LWR fuel has the potential of being transferred into CANDU reactors because it still has a fissile content of 1.4%, higher than the 0.72% U235 concentration in natural uranium. This avenue is currently being investigated jointly by AECL and the Korea Atomic Energy Research Institute with the fuel designated as DUPIC (Direct Use of Spent PWR and BWR Fuel In CANDU) [8-12]. Changing the geometry of the LWR fuel pins to that of CANDU fuel pellets involves no separation of the actinides, providing internationally acceptable processing of the Pu-containing material [11]. Assuming that DUPIC fuel has a parallel behaviour to natural uranium fuel, one would extract energy until ~1.5% additional FPs had been created. This would increase the total energy yield by ~50% from a burnup of 3.4% in LWRs to one close to 5% in the two reactors combined. However, even after this rather substantial gain in energy by his procedure, the used DUPIC fuel would still consist of 95% energy-containing heavy metals.

5.4. MOX fuel

Considerations are underway to blend about 200 tons of Pu239 from disassembled nuclear weapons with depleted uranium (DU) to create mixed oxide fuel (MOX) of plutonium and uranium for CANDU reactors [12]. While this process slowly eliminates weapons-grade plutonium, it creates more used thermal reactor fuel waste. It would be better to blend this plutonium as start-up fuel for fast-neutron reactors, below, to eliminate existing nuclear fuel waste.

6. A different approach to fuel usage – fast neutrons

By creating used nuclear fuel with thermal nuclear reactors, one currently generates an apparent disposal problem of highly radioactive used fuel that must be managed for many tens of thousand years

	Heavy Metal Content %	Current World Inventory tons
Depleted uranium	100	1,800,000
Used CANDU fuel	99.26	40,000
Used LWR fuel	96.6	300,000
Used DUPIC fuel	95	0
	Total	2,140,000

Table 1 Worldwide existing stored quantities of used nuclear fuel actinides (heavy metal)

[2, p341/344]. What is quite obvious, as indicated in the discussion, above, of different fuels for thermal reactors, is that this used fuel waste, and the associated depleted uranium, still consists of 95% to 100% energy-containing uranium and transuranic actinides (Table 1).

If all the stored heavy metal in used LWR fuel were converted to FPs one would gain almost 30 times more energy than had already been extracted. For used CANDU fuel the ratio is 134 times. For all used reactor fuel plus the huge store of depleted uranium one would gain a factor of 200.

6.1. 100,000-fold reduction in long-term radioactivity

Using up the long-lived radioactive transuranic (TRU) actinides in fast-neutron reactors results in a major reduction in the long-term radioactive burden. Figure 1 illustrates the radioactive decay of used CANDU fuel after it leaves the reactor. The curves for FPs and for transuranic actinides are shown in relation to natural uranium. The use of fast-neutron reactors would eliminate all actinides, removing the

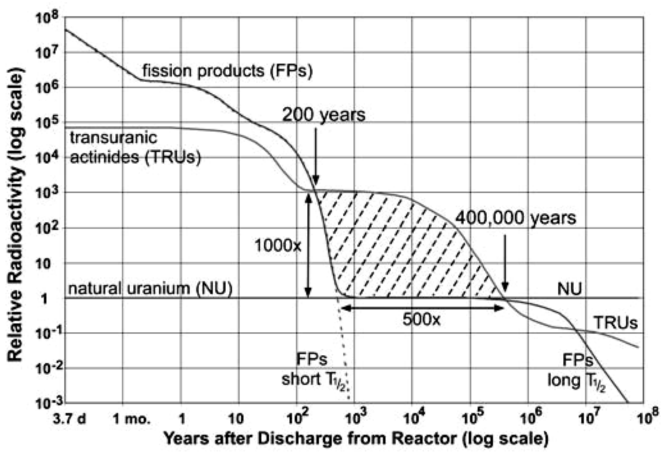

Figure 1 Radioactivity versus time for used CANDU fuel waste (see text)

TRU curve and the uranium line from the graph. The impact is a 100,000-fold reduction in long term radioactive burden of the resulting “waste”, equal to the integral of the area (hatched) between the two curves from 200 to 400,000 years. Note that the log-log representation distorts the area visually.

6.2. Fast-neutron reactor fuel

Fuel for a fast-neutron reactor (FNR) has to be enriched initially with fissile U235, or Pu239/241 to start the neutron chain reaction. Thereafter the fissile concentration is maintained, replaced via neutron capture in U238 and even-numbered transuranics as all of the actinides are consumed, eventually completely (Figure 2).

Fast-neutron reactors exist, both as experimental reactors and as commercial power plants, and have existed since the 1950s when the 200 kWe U.S. EBR-I FNR at the Argonne National Labs created the first electricity from nuclear energy. FNRs can use uranium metal fuel (U.S. 20 MWe EBR-II [20]), or uranium oxide (most other FNRs). Most of these reactors, including the commercial Russian 600 MWe BN-600 reactor operate to a burnup level of 10 to 12% [21].

The experimental EBR-II reactor was used to develop fuel canisters with design changes that increased the burnup from 1 - 3% to 18% [22]. Tests for ultimate fuel container failure showed that fuel breach of the canisters occurred only at a burnup of about 23 – 25%, from a gradual internal pressure buildup of gaseous components in the fission products.

During the 30-year operation of the EBR-II more than 30,000 fuel pins were consumed to the 18% level. When the EBR-II reactor was shut down in 1994, the burnup limit investigations were continued in the French 250 MeV Phenix FNR, achieving a designed safe burnup limit of 25% both for oxide fuel and for metal fuel [23]. Those fuel canisters were not tested to failure.

Enrichment of fuel used in fast-neutron reactors varies from 8% fissile in the 300 MeV sPRISM design of GE-Hitachi [24] to around 20% fissile in the experimental EBR-II [20].

6.3 Theoretical FNR fuel burnup limits

The experiments on safe fuel burnup in the EBR-II and the Phenix FNRs, of 18% and 25% respectively, indicate that at these levels the consumption of fuel was not yet limited by neutron absorption from the buildup of FPs, but by the design of the fuel container. To achieve the greater percentages of fuel consumption, the containers were enlarged for the same absolute fuel charge, to provide an empty volume and so reduce the pressure of gaseous FPs at any given level of burnup.

Since the 25% burnup design was not tested to failure, it is not known if fuel containment would be breached from internal pressure at a higher burnup or whether FP buildup would stop the neutron chain reaction before such a canister failure occurred. To explore the fundamental limits imposed by fission product buildup in fast-neutron reactor fuel, calculations were recently performed on fuel burnup in an idealized container, i.e. one with a very large gas expansion volume [25].

For these calculations the fast-neutron reactor specifications of the sPRISM design of GE-Hitachi [24] were chosen as practical guides. The sPRISM required fuel with a calculated enrichment of about 7% Pu239 or of 9% U235 to maintain an initial neutron equilibrium, in line with the stated design enrichment of 8% [24,25]. The remaining fuel can be used fuel from thermal reactors.

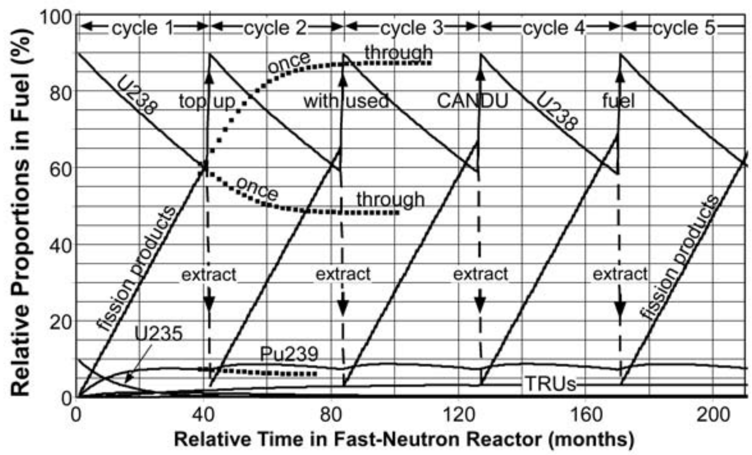

Figure 2 Relative concentrations of U238, fission products, U235, Pu239 and other TRUs with time in a fast-neutron reactor.

Figure 2 shows that in single cycle operation (dotted lines, once through) ~50% of the U238 in used CANDU fuel waste would be consumed along with corresponding amounts of other actinides before neutron absorption from FP buildup would stop the reaction completely. However towards the end the reactor would lose power, and during that loss of power period would also use up more of the fissile material than would be replenished (Pu239, dotted line). For constant power, refueling must occur at a level of about 35% U238 use. At this point the fuel assemblies need to be removed, individually, if the design permits full-power refueling, or altogether. The FPs have to be separated from the actinides, and the latter returned to the reactor. Since the fuel charge is now only 65% of the initial loading, the fuel is topped back up to 100% with used CANDU fuel. No additional fissile material need be added, since this is still sufficient, equivalent to the starting amount, in the separated fuel (see Pu239 line, Fig. 2).

When starting with U235 as fissile component, it takes several cycles for the transuranics to reach equilibrium. Thereafter their concentration remains constant from cycle to cycle. This constancy also means that any used fuel added as top-up at the end of each cycle is completely used up during the next cycle, with all of the added uranium and transuranic elements consumed. At a 35% burnup level of fuel per cycle, one reactor-full of used CANDU fuel waste would be completely eliminated in three cycles.

The separation of the fission products is a key aspect of the process. The most promising approach for such a separation procedure is pyrometallurgical processing, which can recover the actinides with a yield of 99.9% [26]. The actinides need not be entirely free of FPs, since the reactor can obviously be operated with any level of fission products up to around 35 wt% (Fig.2). Allowing some radioactive FPs as impurities in the actinide refuel charge would make the separation procedure less costly. Since actinides are not separated and, in particular, plutonium is not purified, and since a substantial radioactive fraction of FPs remains in the fuel, this process is also quite proliferation resistant.

6.4. Fast-neutron reactor safety

Commercial and research fast-neutron reactors have operated safely for a good number of decades. For instance, the 560 MWe Russian BN-600 started in 1980 and is still running [21]. Its smaller predecessor, the 130 MWe + 150 MWt BN-350 operated from 1972 to 1994 for power and desalination heat. The French 250 MWe research/power FNR Phenix was just shut down in 2009 after operating since 1973, with a potential replacement, the French 600 MWe ASTRID being currently designed.

All of these, similar to thermal reactors, suffered from occasional leaks in the cooling systems. In contrast, the U.S. 20 MWe U.S. experimental EBR-II operated flawlessly from 1964 to its shutdown in 1994 as a result of a political decision [27]. It provided the most extensive information relevant to safety and to utilizing nuclear fuel waste. An entire issue of Nuclear Engineering Design was dedicated to EBR-II safety tests [22,28].

In the most telling of these tests, EBR-II operators deliberately implemented the scenarios that led to the Three-Mile-Island incident in Pennsylvania and to the Chernobyl disaster in the Ukraine. In each case the reactor shut itself down without human or automated intervention, even with intentionally deactivated safety control rods. Its physical design properties made it passively safe [28].

The EBR-II is a design to emulate. Details and first hand insights into its design have been published recently by Leonard Koch [20].

7. Energy Implications

We can assume with certainty from the above discussion that all of the actinides left behind in the manufacture and use of nuclear fuel for and in thermal reactors can be used and consumed completely.

In Canada, the complete consumption of all of the actinides in the currently stored 45,000 tons of used CANDU fuel would produce electricity worth $ 40 trillion at current consumer rates [25]. The current annual electricity production from nuclear energy is worth $9.2 billion at those rates [18]. Therefore the adoption of fast-neutron reactors fueled only by currently stored CANDU fuel waste would result in the production of almost 4000 years of electricity at current levels (Table 2). If fast-neutron nuclear power also replaces all carbon sources of current electrical energy [29], then the used CANDU fuel waste alone would provide such energy for 1600 years.

Nuclear energy currently represents 7% of all energy uses in Canada, while carbon sources of energy comprise 66% [30]. If it were possible to create a non-carbon economy using only nuclear energy to replace carbon, then the energy from fast-neutron reactors refueled only with current used CANDU fuel waste could supplant carbon sources for 380 years.

Similarly, the data in relation to global usage of nuclear energy and carbon-derived energy (Table 2) are based on an annual usage of 12,000 tons of uranium [31,32], the available tonnage of used nuclear fuel and DU, the estimated economic uranium reserves [33], and the combined percent fuel burnup in all reactors from Table 1.

	Canada		World	
	Electricity only	All Energies	Electricity only	All Energies
Current nuclear contribution	15.9%	7%	14%	5.5%
Years of FNR power from used fuel	4000	4000	5700	5700
Current carbon contribution	22.9%	66%	66%	84%
Years of FNR power from used fuel, incl. carbon replacement	1600	380	1005	340
Years of FNR power from used fuel and economic uranium reserves			3500	1200

Table 2 Energy potential of fast-neutron reactors fueled only with stored used CANDU fuel waste (Canada), stored used fuel waste plus depleted uranium (World), and economic uranium reserves (World). Data derived from [18, 29-33]

8. Future fuel resources

The very efficient energy extraction from actinides by fast-neutron reactors means that fuel costs for such reactors become a very minor component of operating costs. Thus, in future, fuel for such reactors could be extracted from sources which today are entirely uneconomical to access. In addition, since nuclear power can be very effectively augmented by other economical renewable and long-term energy sources, the estimates for current and future energy supplies by nuclear power can be stretched to reach further into the future. With such secure energy resources reaching from centuries to thousands of years depending on the mix of energies available, even a doubling of energy demand as many nations develop is not at all a worrisome prospect.

9. Modern alchemy – valuable fission products from uranium

The benefits of the use of fast-neutron reactors for complete consumption of actinides are not merely a 100,000-fold reduction in long-term radioactive burden of the waste, nor just the potential of a 1200-year non-carbon energy economy. In addition many of the fission products, like rhodium, rubidium and scarce rare earth atoms, that are produced from the neutron reactions with heavy atoms, are quite valuable. At current prices the 45,000 tons of FP elements that would result from Canada's stored CANDU fuel waste would fetch over $100 billion [34]. That is a very positive legacy to leave our descendents.

About 30% of the fission products are radioactive. However, the half-life of this residue is close to 500 times shorter than that of used reactor fuel, with most isotopes reaching a natural background level in 300 years or less. A 300-year safe storage for them would therefore be appropriate, since after that wait their mineral "riches" would be extractable by ordinary means. Four atoms, iodine-129, cesium-135, zirconium-93, and technetium-99, are radioactive much longer, but emit only electrons with energies so low that they are easily stopped by a barrier of clear plastic only two millimeters thin.

While fission products from Canada's stored CANDU fuel waste are worth $ 100 billion at today's prices [4], the conversion to fission products of the current worldwide store of used reactor waste and depleted uranium would increase the value of this secondary bonanza from fast-neutron reactors about 50-fold to $ 5.4 trillion. The eventual use of economical uranium reserves would add another $ 13.5 trillion of fission product mineral resources created in fast-neutron reactors.

10. Financing

Funds are being sequestered in all nuclear nations specifically for the disposal of their used nuclear fuel wastes. In Canada funds primarily from the sale of nuclear energy are planned to accumulate to cover the estimated costs of $ 16 to $24 billion for a Deep Geological Repository, the apparent first option for such disposal worldwide.

Since the fast-neutron approach is a very beneficial means of permanently eliminating used nuclear fuel wastes, it seems legitimate to consider the funds designated for their disposal as a source to finance the first demonstrative nuclear-waste-eliminating fast-neutron reactor facility. Such a facility would subsequently be self-supporting and self-propagating from the sale of its nuclear generated electricity and associated heat. Moreover, sited in locations that are currently willing to host a DGR, such a facility would stimulate that local economy and its surroundings with the available electrical power and heat not only for the length of the construction of a would-be DGR, but potentially for centuries.

11. Synopsis

Canada's used CANDU fuel waste as well as the stored used reactor fuel waste worldwide is not a potentially hazardous long-term legacy but an extremely valuable source of energy if consumed as fuel in fast-neutron reactors.

The benefits of such an approach are manifold:

<u>in Canada</u>

- a 100,000-fold reduction in the long-term radioactive burden of the waste
- a $ 36 trillion gain in electricity production from 40,000 tons of used CANDU waste

- a 4000-year supply of nuclear-generated electricity at today's mix of energy sources
- a 1600-year supply of electricity if carbon sources for electricity are replaced by FNR power
- a 380-year supply of energy if carbon sources of all energies are replaced by FNR power
- the elimination of CO_2 from energy production
- the production of 40,000 tons of FP mineral resources worth $ 100 billion today
- the replacement of a potential 1 million-year disposal problem with 300 years of safe storage

worldwide

- a 100,000-fold reduction in the long-term radioactive burden of the waste
- a 5700-year supply of nuclear-generated electricity at today's mix of energy sources
- a 1005-year supply of electricity if carbon sources for electricity are replaced by FNR power
- a 340-year supply of energy if carbon sources of all energies are replaced by FNR power
- the elimination of CO_2 from energy production
- the production of 2,140,000 tons of FP mineral resources worth $ 5.3 trillion today
- the rplacement of a potential 1 million-year disposal problem with 300 years of safe storage

if economical uranium reserves are used as well

- a 3500-year supply of electricity if carbon sources for electricity are replaced by FNR power
- a 1200-year supply of energy if carbon sources of all energies are replaced by FNR power
- the elimination of CO_2 from energy production
- the production of 7,540,000 tons of FP mineral resources worth $ 19 trillion today
- the replacement of a potential 1 million-year disposal problem with 300 years of safe storage

Financing of a nuclear-waste-eliminating fast-neutron reactor facility can legitimately occur via existing and future funds currently designated by law for used nuclear fuel waste disposal.

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