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Impact limits of partitioning and transmutation scenarios on the radiotoxicity of actinides in radioactive waste*

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The used fuel discharged from nuclear power plants constitutes the main contribution to nuclear waste in countries which do not undertake reprocessing. As such, its disposal requires isolation from the biosphere in stable deep geological formations for long periods of time (some hundred thousand years) until its radioactivity decreases through the process of radioactive decay. Ways for significantly reducing the volumes and radiotoxicities of the waste and to shorten the very long times for which the waste must be stored safely are being investigated. This is the motivation behind the partitioning and transmutation (P&T) activities worldwide. This paper addresses the potential impact of P&T on the long-term disposal of nuclear waste. In particular, it evaluates how realistic P&T scenarios can lead to a reduction in the time required for the waste to be stored safely. The calculations have been done independently by three research groups: ITU and FZK in Germany, and by the CEA in France.

Keywords: natural analogues, partitioning & transmutation, radioactivity, research & development, waste management & disposal

Introduction

Nuclear energy provides a significant contribution to the overall energy supply in Europe. With 145 operating reactors producing a total power of 125 GWe, the resulting energy generation of 850 TWh per year provides 35% of the total electrical energy requirements in the European Union.

The used fuel discharged from nuclear power plants constitutes the main contribution to nuclear waste in countries which do not undertake reprocessing. Most of the hazard from the spent fuel stems from only a few chemical elements, namely plutonium, neptunium, americium, curium, and some long-lived fission products such as iodine, caesium and technetium. At present approximately 2500 t of spent fuel are produced annually in the EU, containing about 25 t of plutonium, and 3·5 t of the 'minor actinides' neptunium, americium and curium, and about 3 t of long-lived fission products.

These radioactive by-products, although present in relatively low concentrations in the used fuel, are a hazard to life forms when released into the environment. As such, their disposal requires isolation from the biosphere in stable deep geological formations for long periods of time (some hundred thousand years) until their radioactivity decreases through the process of radioactive decay.

For this reason, in the eyes of some members of the public, nuclear waste disposal could be difficult to accept because of the very long times involving many generations during which this waste must be separated from the biosphere to avoid possible harmful effects. In this context, it is interesting to note, however, that local communities in the Port Hope area (Canada) have recently indicated their willingness to accept nuclear waste on a long-term basis in waste management facilities.[1]

Ways for significantly reducing the volumes and radiotoxicities of the waste and to shorten the very long times for which the waste must be stored safely are being investigated. This is the motivation behind the partitioning and transmutation (P&T) activities worldwide. Partitioning refers to aqueous

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or pyroprocessing methods which are used to separate (partition) the various components of the used fuel: uranium, plutonium, minor actinides, fission products. Transmutation refers to the conversion of a nuclide into one or several other nuclides in a nuclear reactor as a result of neutron-induced fission or capture reactions.

This paper addresses the potential impact of P&T on the long-term disposal of nuclear waste. In particular, it evaluates how realistic P&T scenarios can lead to a reduction in the time required for the waste to be stored safely. The calculations have been done independently by three research groups, namely ITU and FZK in Germany, and by the CEA in France.

Risk and safety

What is meant by risk in connection with the disposal of nuclear waste? This question was recently addressed by a National Academy of Science publication.[2] The analysis of safety involves assessing the likelihood and the severity of harmful events to humans, property, or to the environment. Such a 'risk' analysis involves estimating the harm in terms of the probability of occurrence and the severity of the consequences.

From the viewpoint of the radiotoxicity, which plays a role mainly in accidental intrusion scenarios, P&T must first be concerned with the actinides, particularly the minor actinides, the toxicity of the fission product lying at least two orders of magnitude lower after a few hundred years.

The long-term risk of a geologic repository is, however, usually dominated by fission products which are generally more mobile than the actinides. In the case of nuclear waste disposal, the risk concerned is that of the radionuclides entering the biosphere, for example by groundwater transport. The probability of occurrence of such events is based on computer models which can be very complex. Dose contributions arise primarily from ^{129}I, ^{99}Tc, ^{237}Np, ^{234}U and ^{79}Se, their order of importance depending on the repository concept (see Fig. 1).[3,4] The dose from the US base case repository is from ^{99}Tc and ^{129}I for about the first 50 000 years, after which the dose is primarily from ^{237}Np, an order of magnitude higher than the other contributors.[4] This shows that even if fission products are more mobile in geological repository than actinides, some of them such as ^{237}Np, are also main contributors to the dose rate.

Actinide transmutation strategies address primarily the radiotoxicity (hazard) of the high-level waste (HLW). To reduce the long-term risk (dose to the population), the long-lived fission products would also have to be transmuted or specially transmuted. In addition, the reprocessing of spent nuclear fuel inevitably results in the production of secondary waste (resins, fuel hulls and end pieces, etc.) contaminated with long-lived radionuclides. The long-term management of such waste is highly problematic, and the impact on disposal requires detailed study.

Will P&T make nuclear waste disposal publicly acceptable?

Nuclear waste disposal is a problem of radioactive material 'packaging' in the extreme. One of the challenges facing the nuclear industry is to demonstrate that an underground repository can contain nuclear waste for very long periods of time and that any releases that might take place in the future will pose no significant health or environmental risk. It must be taken into account that the engineered barriers which initially contain the wastes will degrade, and that some residual radionuclides may return to the surface in low concentrations at some time in the future due to groundwater movement and environmental change.

One way of building confidence in engineered barriers is by studying the processes which operate in natural and archaeological systems and by making

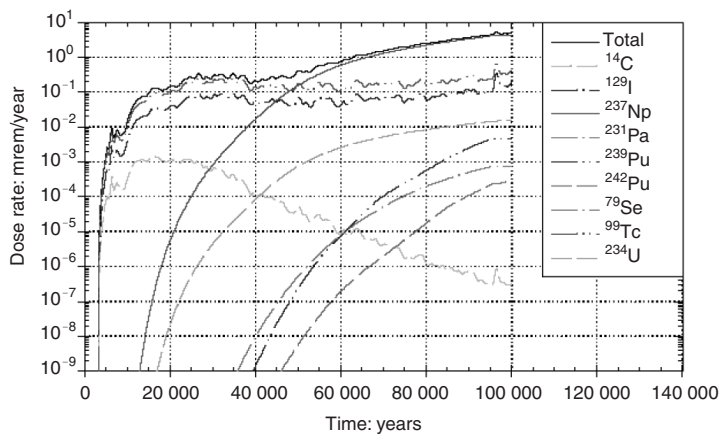

Fig. 1. Expected value dose history over 100 000 years to an individual using water from a well 20 km from the repository[4]

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appropriate parallels with a repository. These studies are called *natural analogues*. In the event that P&T is introduced, the timescales over which the waste must be isolated from the biosphere are much reduced and one can have much greater confidence in the engineered barriers by studying *societal analogues*—that is, society-built structures which have withstood the test of time over a couple of thousand years.

Natural and societal analogues[5]

There are many radioactive materials which occur naturally and can be found in rocks, sediments, etc. In particular, uranium, which is the main component in nuclear fuel, occurs in nature. By studying the distribution in nature, information can be obtained on the movement of uranium in rocks and groundwaters.

Natural analogues provide a way of informing the wider public on the principles on which repositories are built, without using complex mathematical demonstrations of *safety* and *risk*. One of the concepts which can be presented using analogues is the very slow degradation of materials over thousands of years. Some notable analogues are discussed below. (See also Fig. 2.)

The Inchtuthil Roman nails.[6] The most northerly fortress in the Roman Empire at Inchtuthil in Perthshire, Scotland had to be abandoned hastily in 87 AD. In an attempt to hide metal objects which could be used for weapons, the Romans buried over one million nails in a 5 m deep pit and covered them with 3 m of compacted earth. These nails were discovered in the 1950s. It was found that the outermost nails were badly corroded and had formed a solid iron oxide crust. The innermost nails, however, showed only very limited corrosion. This was attributed to the fact that the outer nails removed the oxygen from the infiltrating groundwaters such that by the time they came into contact with the innerlying nails the waters were less corrosive. In the same way, the large volumes of iron in waste canisters are expected to maintain chemically reducing conditions in an environment which might otherwise become oxygen-rich due to the radiolytic decomposition of water.

The Kronan cannon.[7] The Kronan was a Swedish warship built in 1668 and which sank in 1676 during the Battle of Öland. One of the bronze cannons on board the Kronan had remained partly buried in a vertical position, muzzle down in clay sediments since

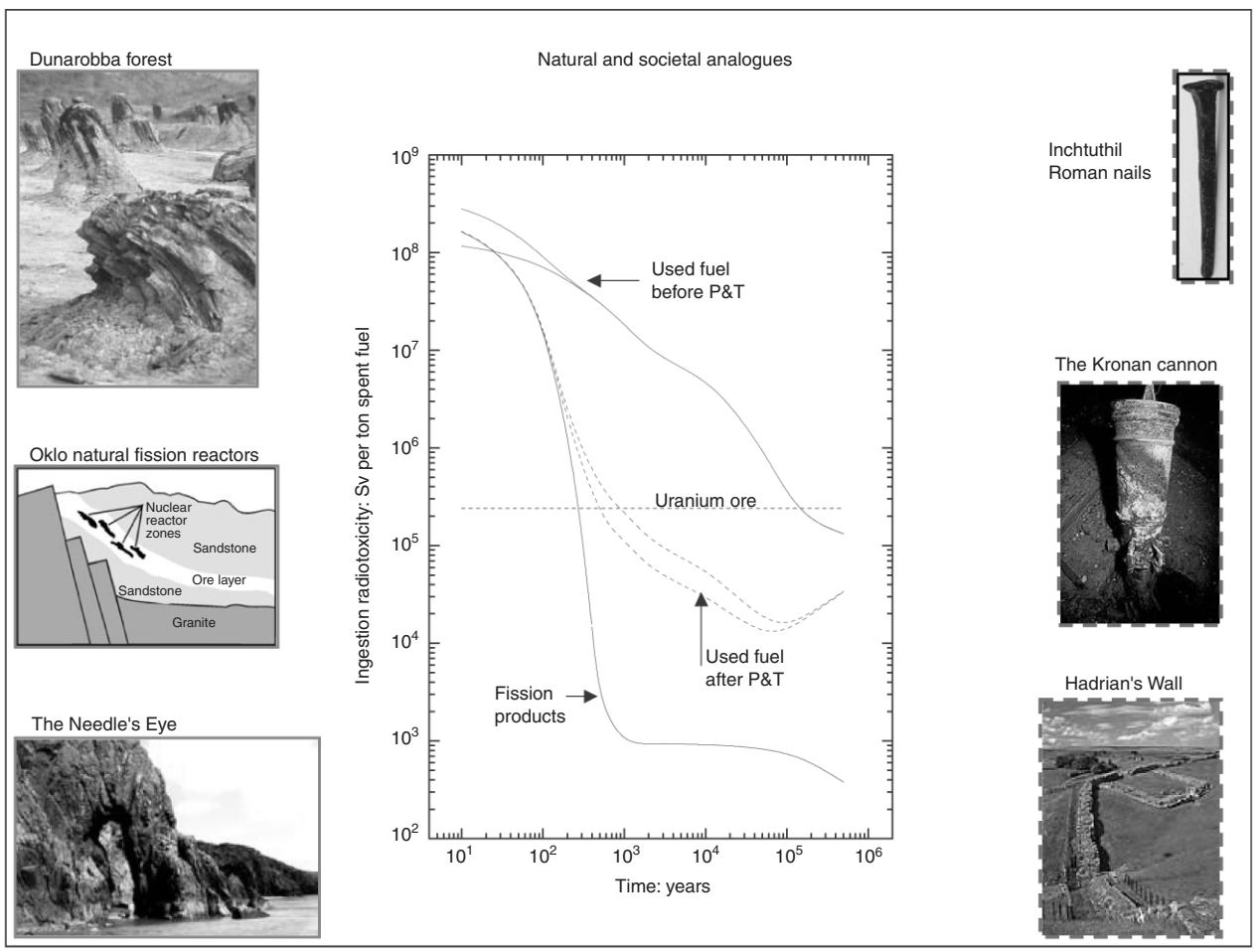

Fig. 2. Will P&T make nuclear waste disposal publicly acceptable?

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the ship sank. This cannon is a good analogue for canisters to be used in the Swedish and Finnish spent fuel repositories which have a copper outer shell, since the cannon had a very high copper content (96·3%). From an analysis of the cannon surface, a corrosion rate of 0·15 μm/year was established. At this rate of corrosion, it would take some 70 000 years to corrode 1 cm thickness of copper. This provides evidence for the very long life of copper spent fuel canisters in the repository.

Hadrian's Wall. In AD 122 Emperor Hadrian ordered construction of a wall to separate the lands of the Britons from that of the Picts to the north. Hadrian's Wall was over 100 km long and 5 m high and was built from stone blocks cemented together. The Wall is of interest as an analogue due to the longevity of Roman cement used to bind the stones together. Modern Portland cement is very similar chemically and mineralogically. From these studies, conclusions can be drawn with regard to the stability and longevity of modern cements in repositories.

The Dunarobba forest. In the Dunarobba forest near Todi in Italy, dead tree trunks approximately 2 million years old have been found in their original upright position. Remarkably, in contrast to typical fossilised trees, the Dunarobba trees are still composed of wood. The wood has been preserved due to the surrounding clay. This clay stopped oxygenated waters from reaching the wood, thereby limiting the aerobic decomposition. The Dunarobba trees are of relevance in repository concepts for low- and intermediate-level wastes since the wood is considered to be analogous to the organic/cellulosic materials which comprise a large part of the waste.

The Needle's Eye.[8] This site in south-west Scotland, close to a natural rock arch known as the Needle's Eye, comprises a sea-cliff in which the mineralised veins of uranium and other metals are partly exposed. Uranium is present as pitchblende (UO_2) associated with secondary minerals.

The pitchblende has undergone dissolution by two processes. In the first, slow leaching results in a preferential loss of ^{234}U relative to ^{238}U. The second is dissolution by oxidising waters. The mobilised uranium is redeposited in close proximity to the vein as stable oxidised uranium minerals. In contrast to uranium, the dissolution and transport of thorium is negligible.

The Needle's Eye is ideal for investigating radionuclide migration behaviour and for testing geochemical codes in simulation exercises.

The Oklo natural fission reactors. In 1972 scientists in France found that the ^{235}U content of ore being processed to make nuclear fuel pellets had been depleted from the normal 0·72% to 0·62%. The ore had been obtained from Oklo in the south-eastern part of the Republic of Gabon in West Africa. Further investigations revealed that nuclear fission had taken place. The uranium ore bodies at Oklo are the only known examples of natural fission reactors. The criticality took place approximately 2 billion years ago as a result of dissolution, mobilisation and accumulation of uranium in sufficient mass to achieve criticality. The chemistry of the uranium is such that it is insoluble in water under oxygen-free conditions, but readily soluble in water in the presence of oxygen. The fission reactions operated intermittently for between 10^5 and 10^6 years.

The natural fission reactors at Oklo can be considered as analogues for very old radioactive waste repositories and can be used to study the transport behaviour of transuranic nuclides and stability of uranium minerals which have undergone criticality.

The P&T efficiency

Before addressing the potential impact that P&T can have on the long-term disposal of nuclear waste, it is useful to introduce the concept of P&T efficiency. Intuitively, if the efficiency of the P&T processing were 100%, all of the harmful products would be separated from the nuclear waste and transformed in short-lived or stable products, thereby avoiding the requirement for a nuclear waste repository. In practice, however, an efficiency of 100% cannot be reached and a repository will be required, albeit for considerable shorter periods of time. But how short is short?

The efficiency of the P&T process is denoted by ε_{PT} ($0 \leq \varepsilon_{PT} \leq 1$) and clearly this is a function of the individual partitioning efficiency ε_P and the transmutation efficiency ε_T. This transmutation efficiency ε_T corresponds to the burnup B of the fuel which is the fraction of the material which has fissioned.

Nuclear waste may have to be recycled many times before it is completely fissioned. In each recycle the partitioning losses are $(1 - \varepsilon_P)$. The number of recycles N is inversely proportional to the transmutation efficiency—that is, $N \sim 1/\varepsilon_T$. (If the transmutation efficiency were 1, only one partitioning step would be required.)

More realistically, the transmutation efficiency may be typically 0·2 (such that approximately five recycles are required for transmutation). It follows that the total losses $(1 - \varepsilon_T)$ are equal to the partitioning losses in one step multiplied by the number of recycles, that is

$$\text{Total losses} = \text{partitioning losses in a single cycle} \times \text{the number of recycles, or}$$

$$(1 - \varepsilon_{PT}) \simeq \frac{(1 - \varepsilon_P)}{\varepsilon_T} \qquad (1)$$

As an example, consider the efficiency of the partitioning process to be $\varepsilon_P = 0{\cdot}999$ (or 99·9%). If the

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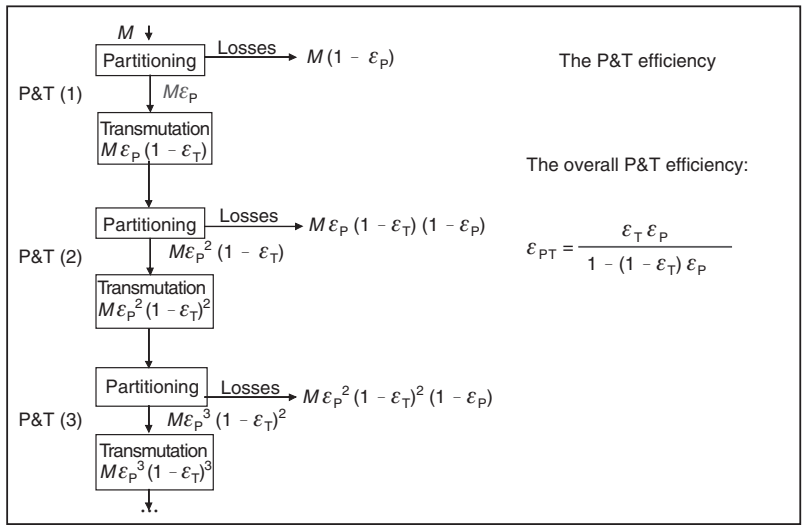

Fig. 3. Multiple recycling of nuclear waste through partitioning and transmutation

efficiency of the transmutation process is $\varepsilon_T = 0{\cdot}20$ (meaning that 20% of the actinides are fissioned in the cycle), then the overall efficiency of the P&T process is

$$\varepsilon_{PT} \simeq 1 - \frac{(1-\varepsilon_P)}{\varepsilon_T} = 0{\cdot}995 \text{ (or } 99{\cdot}5\%) \qquad (2)$$

In a more detailed analysis, as shown in Fig. 3, the effect of multiple recycling can be investigated. Consider a reactor loaded initially with a mass M of fresh fuel. In a first step, the separation of the different waste streams is done, and a fraction $(M\varepsilon_P)$ is irradiated while the remaining fraction $[M(1-\varepsilon_P)]$ leaves for processing. Following the irradiation, a fraction $[M\varepsilon_P(1-\varepsilon_T)]$ is reprocessed, and the fraction $[M\varepsilon_P(1-\varepsilon_T)(1-\varepsilon_P)]$ goes to the waste and the remaining fraction $[M(1-\varepsilon_T)\varepsilon_P^2]$ is recycled for a new irradiation. This process can be repeated indefinitely. It follows that the total losses are given by

$$\begin{aligned}(1-\varepsilon_{PT})M &= M(1-\varepsilon_P) + M\varepsilon_P(1-\varepsilon_T)(1-\varepsilon_P) \\ &\quad + M(1-\varepsilon_T)^2(1-\varepsilon_P)\varepsilon_P^2 + \cdots \\ &= M(1-\varepsilon_P)[1+\varepsilon_P(1-\varepsilon_T) + \varepsilon_P^2(1-\varepsilon_T)^2 + \cdots] \\ &= \frac{M(1-\varepsilon_P)}{[1-\varepsilon_P(1-\varepsilon_T)]} \qquad (3)\end{aligned}$$

or

$$\varepsilon_{PT} = \frac{\varepsilon_P\varepsilon_T}{1-(1-\varepsilon_T)\varepsilon_P} \qquad (4)$$

As an example consider the case: $\varepsilon_P = 0{\cdot}999$ (99·9% separation efficiency), $\varepsilon_T = 0{\cdot}20$ (meaning that 20% of the actinides are fissioned in the cycle), hence $\varepsilon_{PT} = 0{\cdot}995$ (99·5% effective separation efficiency).

Using the infinite summation method, one follows an initial batch of actinides through all the successive burnups, reprocessings and recyclings and sums up all the losses that occur at each of the reprocessings.

Standardised burnup calculations

Radiotoxicity and effective dose coefficients

A measure of the potential hazard of nuclear material is provided by the *toxicity* and in particular its radiotoxicity arising from its radioactive quality rather than the chemical toxicity. The radiotoxicity of a nuclide is determined by its effective dose coefficient $e(T)$, which accounts for radiation and tissue weighting factors, metabolic and biokinetic information. The quantity T is the integration time in years following intake. For adults, the integration time is 50 years, such that the radiotoxicity (in sievert, Sv) resulting from intake of a particular nuclide is the product of the effective dose coefficient (units Sv/Bq) and the activity (in Bq) of that nuclide, that is

$$\text{Radiotoxicity} = \text{Activity} \times e(50) \qquad (5)$$

In many computer codes the older values of effective dose coefficients from ICRP68[9] are in use. In 1996 these values were updated in a new publication, ICRP72.[10]

Whereas most of the differences between the ICRP68 and ICRP72 values are small, there are two exceptions. For ^{210}Po, there is a very big increase from $2{\cdot}4 \times 10^{-7}$ in ICRP68 to $1{\cdot}2 \times 10^{-6}$ in ICRP72. For ^{93}Zr there is an increase from $2{\cdot}8 \times 10^{-10}$ Sv in ICRP68 to $1{\cdot}1 \times 10^{-9}$ Sv in ICRP72. The different values for ^{210}Po lead to a significant change in the reference radiotoxicity since ^{210}Po is a daughter product of ^{238}U.

Burn-up calculations

Standardised burnup calculations have been carried

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Table 1. Standardised burnup calculations (4·2% enrichment, 50 GWd/t, 6 years cooling time): actinide mass (g) inventory per ton of spent fuel

Nuclide	Fresh fuel	FZK (F) KORIGEN (Biblis)	ITU (I) ORIGEN2 (PWRUS50)	CEA (C) APOLLO2 (JEF2·2)	(F − I)/F: %	(C − I)/C: %	(F − C)/F: %
^{235}U	$4{\cdot}20 \times 10^{4}$	$6{\cdot}96 \times 10^{3}$	$6{\cdot}86 \times 10^{3}$	$7{\cdot}60 \times 10^{3}$	1·5	9·8	−9·2
^{236}U		$5{\cdot}59 \times 10^{3}$	$5{\cdot}65 \times 10^{3}$	$5{\cdot}46 \times 10^{3}$	−1·1	−3·5	2·3
^{238}U	$9{\cdot}58 \times 10^{5}$	$9{\cdot}24 \times 10^{5}$	$9{\cdot}24 \times 10^{5}$	$9{\cdot}22 \times 10^{5}$	0·0	−0·2	0·2
^{237}Np		$7{\cdot}27 \times 10^{2}$	$7{\cdot}61 \times 10^{2}$	$7{\cdot}00 \times 10^{2}$	−4·6	−8·7	3·8
^{238}Pu		$3{\cdot}35 \times 10^{2}$	$3{\cdot}12 \times 10^{2}$	$3{\cdot}39 \times 10^{2}$	7·1	8·1	−1·1
^{239}Pu		$5{\cdot}66 \times 10^{3}$	$5{\cdot}86 \times 10^{3}$	$6{\cdot}09 \times 10^{3}$	−3·6	3·7	−7·6
^{240}Pu		$2{\cdot}73 \times 10^{3}$	$2{\cdot}73 \times 10^{3}$	$2{\cdot}84 \times 10^{3}$	0·0	3·9	−4·1
^{241}Pu		$1{\cdot}22 \times 10^{3}$	$1{\cdot}30 \times 10^{3}$	$1{\cdot}33 \times 10^{3}$	−6·0	2·5	−8·7
^{242}Pu		$8{\cdot}42 \times 10^{2}$	$8{\cdot}52 \times 10^{2}$	$8{\cdot}59 \times 10^{2}$	−1·2	0·8	−2·0
^{241}Am		$4{\cdot}64 \times 10^{2}$	$4{\cdot}87 \times 10^{2}$	$5{\cdot}02 \times 10^{2}$	−4·8	3·1	−8·1
^{242m}Am		$8{\cdot}42 \times 10^{-1}$	$1{\cdot}16 \times 10^{0}$	$9{\cdot}02 \times 10^{-1}$	−37·8	−28·6	−7·2
^{243}Am		$1{\cdot}92 \times 10^{2}$	$2{\cdot}11 \times 10^{2}$	$2{\cdot}05 \times 10^{2}$	−9·8	−3·1	−6·5
^{242}Cm		$4{\cdot}38 \times 10^{-3}$	$4{\cdot}98 \times 10^{-3}$	$4{\cdot}64 \times 10^{-3}$	−13·7	−7·2	−6·0
^{243}Cm		$5{\cdot}60 \times 10^{-1}$	$8{\cdot}21 \times 10^{-1}$	$6{\cdot}56 \times 10^{-1}$	−46·5	−25·1	−17·1
^{244}Cm		$6{\cdot}22 \times 10^{1}$	$7{\cdot}08 \times 10^{1}$	$7{\cdot}15 \times 10^{1}$	−13·8	1·0	−14·9
^{245}Cm		$2{\cdot}86 \times 10^{0}$	$4{\cdot}30 \times 10^{0}$	$6{\cdot}11 \times 10^{0}$	−50·5	29·6	−113·8
^{246}Cm		$3{\cdot}61 \times 10^{0}$	$6{\cdot}78 \times 10^{-1}$	$7{\cdot}62 \times 10^{-1}$	81·2	11·1	78·9
Total	$1{\cdot}00 \times 10^{6}$	$9{\cdot}49 \times 10^{5}$	$9{\cdot}49 \times 10^{5}$	$9{\cdot}48 \times 10^{5}$			

out by three different organisations: ITU, FZK and CEA. The results for the actinide mass inventories are given in Tables 1 and 2 for the actinides and fission products respectively. The burnup calculations were based on a 4·2% enrichment of ^{235}U in ^{238}U, a burnup of 50 GWd/tM and six years cooling time. The codes/libraries used (KORIGEN/Biblis, ORIGEN2/PWRUS50, and APOLLO2/JEF2.2) are standard codes and cross-section libraries for such calculations.

Actinides. The actinide mass inventory resulting from burnup and cooling is given in Table 1. In the last three columns, a comparison of the results is made of the ITU, FZK, and CEA results. There is good agreement on the actinide mass inventories from the various codes used by ITU, FZK and CEA for the standard calculation (4·2% enrichment, 50 GWd/t, 6 years cooling time).

- For U and Pu isotopes, agreement is better than ±10%.
- For Am isotopes, agreement is better than ±20%.
- For ^{242}Cm and ^{244}Cm, agreement is reasonable (±25%), but less good for ^{245}Cm and ^{246}Cm (±70%).

The results are also compared in Figs 4 and 5.

Fission products. The results for the fission product inventories are given in Table 2. Very short- and long-lived products have been omitted. The results of the decay calculations are given in the next section.

Actinide decay and radiotoxicity calculations

Actinide ingestion radiotoxicity plotted against time

Based on the ICRP72 values for the effective dose coefficients, the total actinide ingestion radiotoxicity plotted against time is shown in Fig. 6. The ITU results, obtained with Nuclides.net,[11] are compared to the FZK and CEA results. The results are in good agreement (see inset in Fig. 6). On the logarithmic plot the small differences between the results do not show up.

It is also of interest to see how the main components contribute to the total ingestion radiotoxicity. This is shown in Fig. 7 for the ITU data, where the results are grouped according to chemical element present after six years cooling (the data are given in Table 3 of the appendix). Notice that 'U' refers to the sum of all uranium isotopes at time six years. At later times the uranium isotopes decay to other chemical elements which are also accounted for in the 'U' curve. The advantage of grouping in this manner is that it is easier to see the effects of partitioning.

As can be seen from Fig. 7, the total ingestion radiotoxicity arises from the plutonium isotopes (present after six years cooling!). Around 200 years, the Pu radiotoxicity is $4{\cdot}3 \times 10^{7}$ Sv (from Table 3)—that is, a factor 180 ($4{\cdot}3 \times 10^{7}/2{\cdot}4 \times 10^{5}$) above the reference value indicated by the dashed line (discussed in detail in the following section). Conversely, to reduce the waste toxicity to reference levels in this timescale, the effective Pu removal efficiency needs to be 0·994 (i.e. $1 - 1/180$). Similarly at 200 years, the americium radiotoxicity is $9{\cdot}4 \times 10^{6}$ Sv—that is, a factor 40 higher than the reference level. Hence an effective removal efficiency needs to be approximately

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Table 2. Standardised burnup calculations (4·2% enrichment, 50 GWd/t, 6 years cooling time): mass (g) inventory per ton of spent fuel of fission products with half-lives in the range 0·5–10^{15} years

Fission product	Half-life	FZK	ITU	CEA
^{3}H	12·34 y	$4{\cdot}91 \times 10^{-2}$	$6{\cdot}07 \times 10^{-2}$	$5{\cdot}08 \times 10^{-2}$
^{10}Be	$1{\cdot}5 \times 10^{6}$ y	$1{\cdot}41 \times 10^{-2}$	$1{\cdot}96 \times 10^{-4}$	—
^{14}C	$5{\cdot}7 \times 10^{3}$ y	$4{\cdot}37 \times 10^{-3}$	$3{\cdot}96 \times 10^{-5}$	$4{\cdot}37 \times 10^{-3}$
^{79}Se	$6{\cdot}5 \times 10^{5}$ y	$3{\cdot}20 \times 10^{0}$	$8{\cdot}75 \times 10^{0}$	$7{\cdot}16 \times 10^{0}$
^{81}Kr	$2{\cdot}3 \times 10^{5}$ y	$1{\cdot}46 \times 10^{-5}$	$4{\cdot}26 \times 10^{-5}$	$1{\cdot}57 \times 10^{-5}$
^{85}Kr	10·76 y	$2{\cdot}45 \times 10^{1}$	$2{\cdot}33 \times 10^{1}$	$2{\cdot}39 \times 10^{1}$
^{87}Rb	$4{\cdot}8 \times 10^{10}$ y	$3{\cdot}49 \times 10^{2}$	$3{\cdot}59 \times 10^{2}$	$3{\cdot}47 \times 10^{2}$
^{90}Sr	28·86 y	$6{\cdot}79 \times 10^{2}$	$6{\cdot}73 \times 10^{2}$	$6{\cdot}62 \times 10^{2}$
^{93}Zr	$1{\cdot}5 \times 10^{6}$ y	$1{\cdot}05 \times 10^{3}$	$1{\cdot}06 \times 10^{3}$	$1{\cdot}03 \times 10^{3}$
^{93m}Nb	16·1 y	$3{\cdot}02 \times 10^{-3}$	$2{\cdot}96 \times 10^{-3}$	$3{\cdot}16 \times 10^{-3}$
^{94}Nb	$2{\cdot}0 \times 10^{4}$ y	$6{\cdot}86 \times 10^{-4}$	$1{\cdot}15 \times 10^{-3}$	$6{\cdot}64 \times 10^{-4}$
^{97}Tc	$2{\cdot}6 \times 10^{6}$ y	$2{\cdot}19 \times 10^{-7}$	—	—
^{98}Tc	$4{\cdot}2 \times 10^{6}$ y	$1{\cdot}61 \times 10^{-3}$	$1{\cdot}37 \times 10^{-2}$	$1{\cdot}50 \times 10^{-5}$
^{99}Tc	$2{\cdot}1 \times 10^{5}$ y	$1{\cdot}18 \times 10^{3}$	$1{\cdot}09 \times 10^{3}$	$1{\cdot}15 \times 10^{3}$
^{106}Ru	1·02 y	$3{\cdot}25 \times 10^{0}$	$3{\cdot}72 \times 10^{0}$	$3{\cdot}60 \times 10^{0}$
^{107}Pd	$6{\cdot}5 \times 10^{6}$ y	$3{\cdot}35 \times 10^{2}$	$3{\cdot}53 \times 10^{2}$	$3{\cdot}53 \times 10^{2}$
^{108m}Ag	$4{\cdot}2 \times 10^{2}$ y	$3{\cdot}03 \times 10^{-6}$	$1{\cdot}81 \times 10^{-6}$	$3{\cdot}39 \times 10^{-6}$
^{110m}Ag	$2{\cdot}5 \times 10^{2}$ d	$1{\cdot}39 \times 10^{-3}$	$3{\cdot}82 \times 10^{-3}$	$3{\cdot}78 \times 10^{-3}$
^{109}Cd	1·27 y	$3{\cdot}67 \times 10$	$5{\cdot}20 \times 10^{-8}$	$4{\cdot}40 \times 10^{-13}$
^{113m}Cd	14·11 y	$2{\cdot}48 \times 10^{-1}$	$3{\cdot}31 \times 10^{-1}$	$1{\cdot}35 \times 10^{-1}$
^{115}In	$4{\cdot}4 \times 10^{14}$ y	$2{\cdot}59 \times 10^{0}$	$2{\cdot}56 \times 10^{0}$	$2{\cdot}44 \times 10^{0}$
^{119m}Sn	$2{\cdot}9 \times 10^{2}$ d	$8{\cdot}38 \times 10^{-5}$	$1{\cdot}43 \times 10^{-4}$	$9{\cdot}62 \times 10^{-5}$
^{121m}Sn	55·04 y	$6{\cdot}85 \times 10^{-2}$	$5{\cdot}05 \times 10^{-3}$	$7{\cdot}48 \times 10^{-1}$
^{126}Sn	$2{\cdot}1 \times 10^{5}$ y	$3{\cdot}58 \times 10^{1}$	$4{\cdot}14 \times 10^{1}$	$4{\cdot}54 \times 10^{1}$
^{125}Sb	2·76 y	$4{\cdot}21 \times 10^{0}$	$4{\cdot}36 \times 10^{0}$	$4{\cdot}47 \times 10^{0}$
^{123}Te	6×10^{14} y	$4{\cdot}89 \times 10^{-3}$	$2{\cdot}07 \times 10^{-2}$	$9{\cdot}11 \times 10^{-3}$
^{129}I	$1{\cdot}6 \times 10^{7}$ y	$2{\cdot}37 \times 10^{2}$	$2{\cdot}67 \times 10^{2}$	$2{\cdot}72 \times 10^{2}$
^{134}Cs	2·07 y	$2{\cdot}71 \times 10^{1}$	$3{\cdot}09 \times 10^{1}$	$2{\cdot}97 \times 10^{1}$
^{135}Cs	$2{\cdot}3 \times 10^{6}$ y	$5{\cdot}75 \times 10^{2}$	$5{\cdot}39 \times 10^{2}$	$5{\cdot}94 \times 10^{2}$
^{137}Cs	30·09 y	$1{\cdot}57 \times 10^{3}$	$1{\cdot}56 \times 10^{3}$	$1{\cdot}57 \times 10^{3}$
^{133}Ba	10·52 y	$3{\cdot}08 \times 10^{-8}$	$0{\cdot}00 \times 10^{0}$	—
^{138}La	$1{\cdot}1 \times 10^{11}$	$3{\cdot}43 \times 10^{-3}$	$1{\cdot}41 \times 10^{-1}$	—
^{144}Ce	$2{\cdot}8 \times 10^{2}$ d	$1{\cdot}77 \times 10^{0}$	$2{\cdot}06 \times 10^{0}$	$1{\cdot}97 \times 10^{0}$
^{147}Pm	2·63 y	$4{\cdot}41 \times 10^{1}$	$3{\cdot}06 \times 10^{1}$	$4{\cdot}45 \times 10^{1}$
^{145}Sm	340 d	$2{\cdot}31 \times 10$	$0{\cdot}00 \times 10^{0}$	—
^{146}Sm	$1{\cdot}0 \times 10^{8}$ y	$9{\cdot}58 \times 10^{-3}$	$1{\cdot}42 \times 10^{-2}$	—
^{147}Sm	$1{\cdot}1 \times 10^{11}$ y	—	$2{\cdot}00 \times 10^{2}$	$2{\cdot}78 \times 10^{2}$
^{151}Sm	90 y	—	$1{\cdot}82 \times 10^{1}$	$1{\cdot}71 \times 10^{1}$
Total mass (g)	—	$6{\cdot}12 \times 10^{3}$	$6{\cdot}27 \times 10^{3}$	$6{\cdot}44 \times 10^{3}$

0·975 (1 − 1/40). The 'Np' and 'U' curves fall far below the reference levels.

For curium, it can be seen that the radiotoxicity around 200 years is actually below the reference level—indication that it may not be necessary to remove it from the waste. Nevertheless, this depends on the P&T strategy followed for the other waste streams. The Cm radiotoxicity follows, from 200 years until 5000 years, a plateau around the value of 10^5 Sv. If the separation and transmutation of the plutonium and americium is efficient enough to reduce significantly the total radiotoxicity of the waste then the curium could be left in the waste (its own radiotoxicity is then below the reference level). But it should be borne in mind that even if, after the separation and transmutation of plutonium and americium, the radiotoxicity of each of the waste streams such as Pu, Am and Cm reaches a value of 10^5 Sv, a value which is below the reference level, the total radiotoxicity of the three waste streams would still be more than 3×10^5 Sv, a value which is above the reference level. In this case a separation of the curium from the waste would be a necessity in order to reduce the total radiotoxicity to the reference level.

The radiotoxicity reference level

To produce 1 t of fresh fuel with an enrichment of 4·2% ^{235}U, 7·83 t of natural uranium are required. This amount is determined from the enrichment balance conditions

$$\begin{aligned} U_{Feed} &= U_{Product} + U_{Tails}, \\ {}^{235}U_{Feed} &= {}^{235}U_{Product} + {}^{235}U_{Tails} \end{aligned} \tag{6}$$

Leading to

$$U_{Feed} = \frac{\varepsilon_{Product} - \varepsilon_{Tails}}{\varepsilon_{Feed} - \varepsilon_{Tails}} U_{Product} \tag{7}$$

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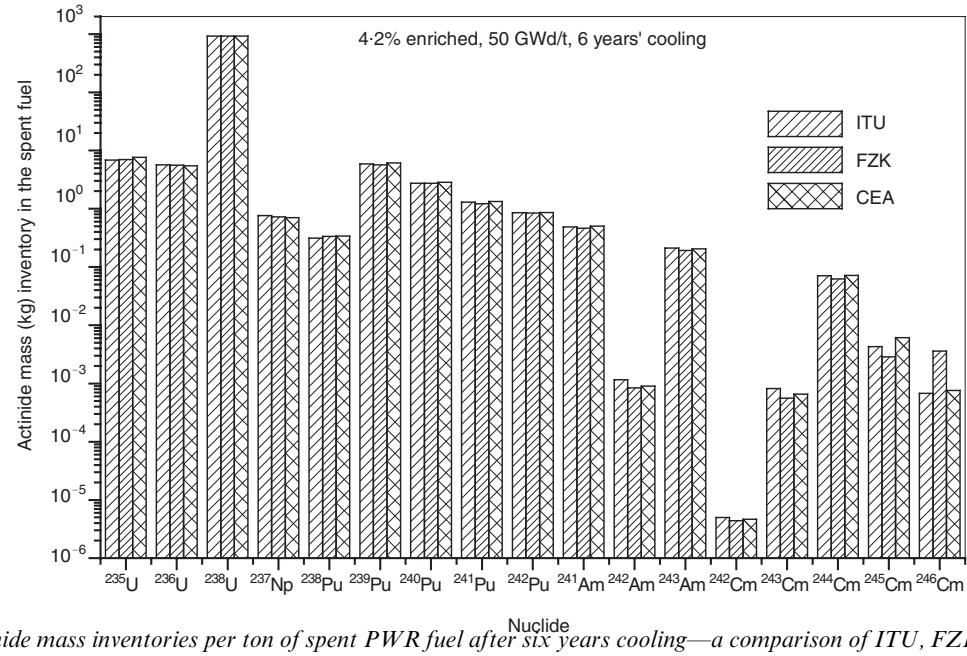

Fig. 4. Actinide mass inventories per ton of spent PWR fuel after six years cooling—a comparison of ITU, FZK and CEA results

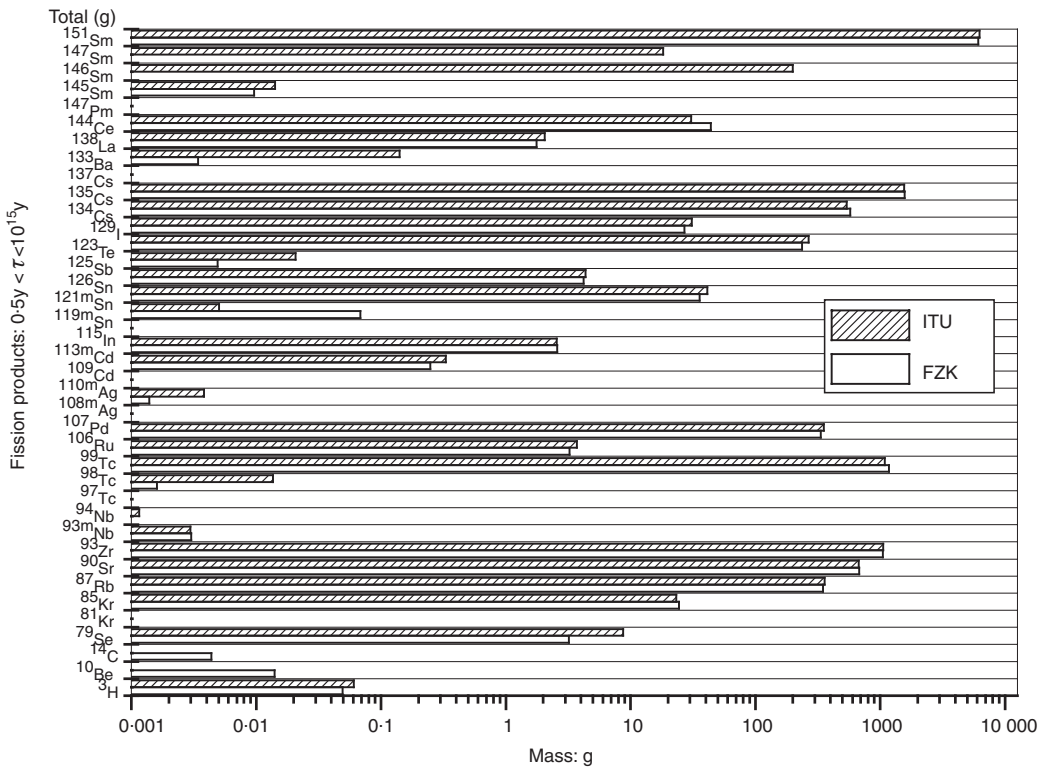

Fig. 5. Comparison of fission products after burnup (at six years cooling)

where $\varepsilon_{Product} = {}^{235}U_{Product}/U_{Product}$ is the enrichment of the product uranium, $\varepsilon_{Feed} = {}^{235}U_{Feed}/U_{Feed}$ is the enrichment of the feed uranium, $\varepsilon_{Tails} = {}^{235}U_{Tails}/U_{Tails}$ is the enrichment of the tails uranium. The enrichments $\varepsilon_{Product} = 4{\cdot}2\%$, $\varepsilon_{Feed} = 0{\cdot}711\%$, $\varepsilon_{Tails} = 0{\cdot}2\%$ and the desired amount of enriched uranium of $U_{Product} = 1$ t result in $U_{Feed} = 7{\cdot}83$ t natural uranium.

For this reason the ingestion radiotoxicity of 7·83 t of natural uranium, in equilibrium with its daughter products, is considered as the reference level in the calculations. The resulting ingestion radiotoxicity is then $2{\cdot}41 \times 10^5$ Sv based on the ICRP72[10] values for the effective dose coefficient. Had the ICRP68[9] values been taken, a lower value of $1{\cdot}47 \times 10^5$ Sv would have resulted. The main reason for this difference is due to

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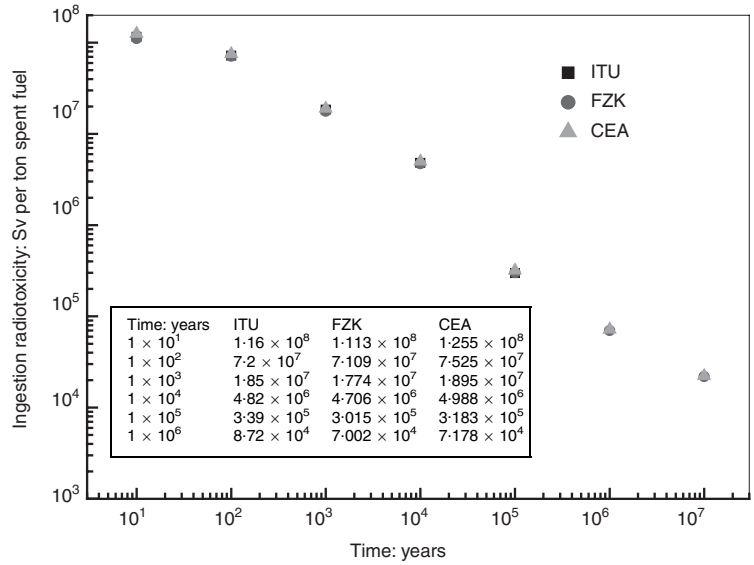

Fig. 6. Actinide ingestion radiotoxicity of spent PWR fuel—a comparison of ITU, FZK and CEA results

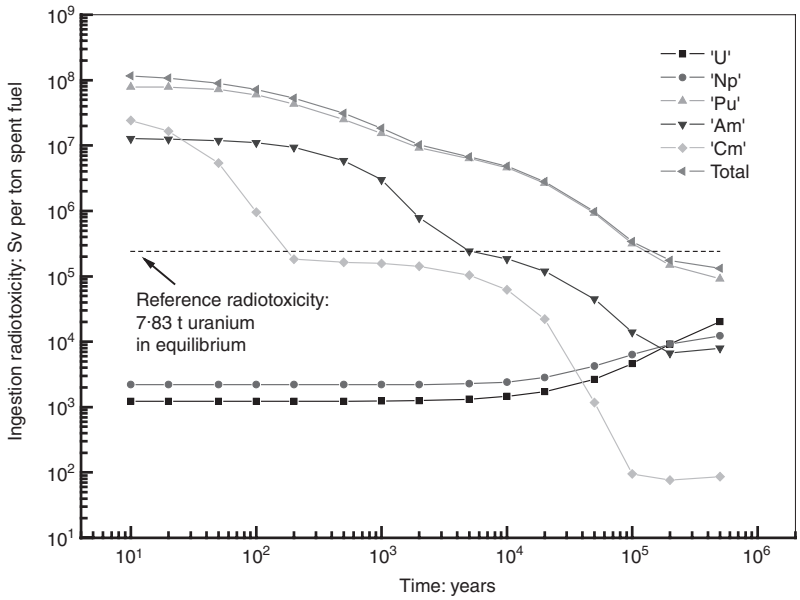

Fig. 7. Actinide mass inventories in spent PWR fuel plotted against time (ITU data). Results are grouped by element, present after six years cooling. (Results based on ICRP72[10])

the much higher effective dose coefficient for ^{210}Po given in ICRP72.

Based on the ICRP72[10] values, the time to reach the reference toxicity level is 130 000 years. Using the ICRP68[9] values this time would increase to 170 000 years.

Radiotoxicity reduction in different P&T strategies

To investigate the effects of different P&T strategies on the radiotoxicity reduction, three cases have been considered in this study, as well as the open cycle. The resulting radiotoxicity curves are shown in Fig. 8, in which the crossover point indicates the time at which the radiotoxicity of the waste reaches the reference level. The following observations can be made.

(*a*) The open cycle: the spent fuel is directly sent to long-term storage with no P&T. It takes 130 000 years before the radiotoxicity reaches the reference level.

(*b*) The full multi-recycling of Pu as well as Am and Cm with high overall efficiency of P&T processes (99·5% for Pu and 99% for Am + Cm). The

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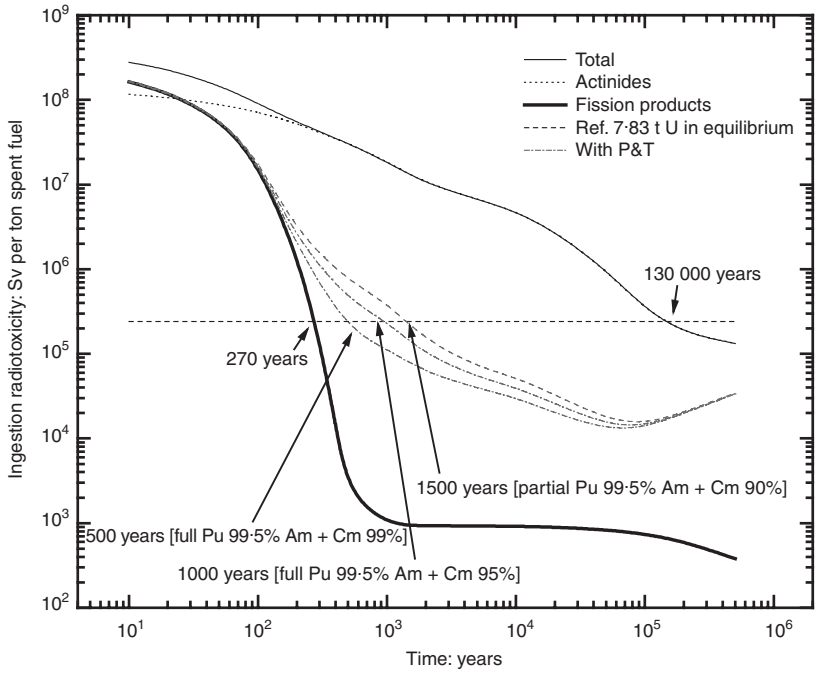

Fig. 8. Ingestion radiotoxicity of one ton used nuclear fuel based on ICRP72 effective dose coefficients

crossover point is 500 years. If the Cm is left in the waste, this time is extended to 1000 years.

(*c*) The full multi-recycling of Pu as well as Am and Cm with less overall efficiency of P&T processes (99·5% for Pu and 95% for Am + Cm). The crossover point is 1000 years.

(*d*) The partial multi-recycling: multi-recycling of the Pu (99·5% of P&T efficiency), and one single recycling of the Am and Cm. In this case the Am and Cm are transmuted in targets in a fast reactor, and then 90% of P&T overall efficiency is foreseen. Thus the crossover point is around 1500 years. In this strategy, we can also consider leaving the Cm in the waste, and then 3000 years are required.

Based on these results it can be concluded that P&T can help reduce the radiotoxicity of the spent fuel by more than two orders of magnitude after 500 to 1500 years. The fission products radiotoxicity curve gives the theoretical limit to the total radiotoxicity reduction in the case that all the actinides are partitioned and transmuted—that is, no losses. This time is about 270 years to reach the same order of magnitude in the radiotoxicity reduction.

P&T strategy technical feasibility[12]

Feasibility of the partial multi-recycling strategy

The partial multi-recycling strategy (Fig. 9) consists of the multi-recycling of the Pu and Np in fast reactors associated with one single recycle of Am and perhaps Cm. Targets containing small amounts of Am (and maybe Cm) would be placed in the fast reactor and irradiated during a long period of time.

This strategy requires the knowledge and demonstration of advanced aqueous reprocessing of spent oxide fuel, to recover Pu, Np, Am and Cm. The reprocessing in current (but modified) installation requires high separation rates (99·9% for Pu and Np, and 99% for Am and Cm), which seems feasible from present research results.[13] The separation efficiency of several actinides demonstrates that 99·9% of recovery is achievable for Pu, Np and Am with the DIAMEX process.[13] One open question is the treatment of the Cm. If the Cm is not transmuted while the Am is, then the separation of the Cm from Am has to be done, which needs further experimental demonstration. In this case Cm must be conditioned and decay to Pu, which could be further transmuted if necessary.

After separation, the minor actinides have to be conditioned preferably in stable U-free targets for their irradiation in fast reactors for their transmutation by fission. The development of the facilities and fabrication processes are going on mainly at ITU and CEA for Europe, and the feasibility of their fabrication, transmutation and good irradiation behaviour has been partially demonstrated.[14] New experiments planned in Phenix and HFR will further increase the present database[15] and more experiments will still be required before considering these new compounds for licensing in commercial installations and for large-scale utilisation. This can be achieved within a couple of decades taking into account the long lead-time

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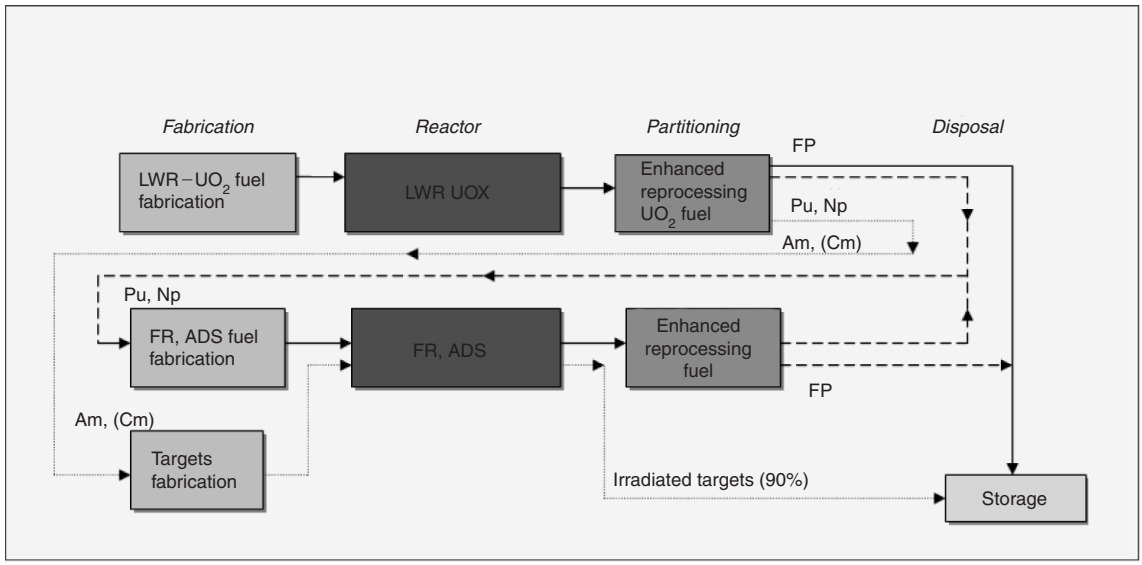

Fig. 9. Flow sheet of the partial multi-recycling strategy

needed in reactor materials developments. A particular technical question to be resolved in this strategy is the high transmutation rate required: the amount of actinides still present in the irradiated targets should be less than 10% of the actinides initially loaded. This requires high burning rates, and the demonstration that the materials, fuel and cladding, can sustain these limits without failure.

Feasibility of the full multi-recycling strategy

The full multi-recycle strategy (Fig. 10) consists of the multi-recycling of Pu, Np, Am, and possibly Cm in a dedicated reactor. This strategy is preferable from the societal point of view since it can potentially lead to radiotoxicity reduction factors of more than 100 after only 500 years instead of a few thousands of years in the heterogeneous strategy and several hundred thousands of years if P&T is not applied.

As concluded by the European Technical Working Group on ADS,[16] this goal necessitates first the design of suitable reactors, preferably dedicated ones, as well as improved fuel cycle requirements. Let us concentrate here on the latter. The first strata reprocessing is comparable to that of the partial multi-recycling strategy, and seems feasible in the medium term. The reprocessing of the second strata materials will in any case require separate installations, due to the different nature of the materials to be reprocessed: they contain large amounts of residual transuranium elements, and they are probably embedded in U-free matrices to

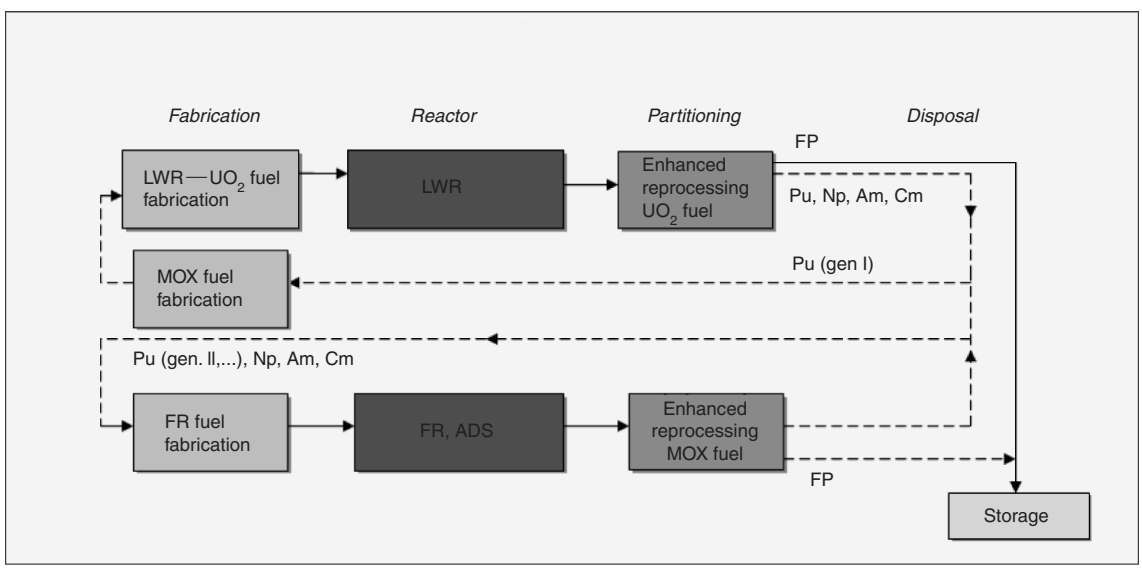

Fig. 10. Flow sheet of the full multi-recycling strategy

avoid excessive production of such elements from neutron absorption in U. These inert matrices are not yet totally defined: oxides (zirconia-based) and nitrides are envisaged in Europe.[17] They all have advantages and drawbacks, among others the reprocessability of non-U oxides. Oxide-to-metal reduction followed by electrorefining is now under development at ITU and CEA and other laboratories, but feasibility is not demonstrated yet at a larger scale.

The fuel fabrication does not bring additional difficulties as compared to the partial multi-recycling strategy. Only the quantities involved are increased, and larger facilities will have to be considered in the future. On the contrary, the burning rate to be achieved is smaller (20%), and fuel design and licensing could be simplified. An important concern related to P&T in general and to the full multi-recycling strategy in particular, is the secondary wastes production. It comprises all insoluble active residues, degraded solvents or salts, ancillary materials, analytical wastes, activation and spallation products in the case of accelerator-driven systems (ADS), etc. Any P&T implementation scenario will have to consider the wastes and provide feasible technical solutions for their conditioning and storage.

Taking into account these considerations, a large-scale demonstration of the full multi-recycle strategy cannot be envisaged before a couple of decades from now. However, one could envisage as a compromise a simplification of the best technical options, by using U matrices, as already demonstrated on a small scale more than ten years ago with SUPERFACT. U, Pu, MA oxide-based fuels require less (although not negligible) design, fabrication and licensing efforts.

Dose to the personnel

Preliminary and approximate estimations of the additional exposures of workers due to the introduction of the P&T cycle have been given.[18] An increase is expected for the fuel cycle due to the handling of highly radioactive elements in the fabrication and reprocessing plants, as well as fuel transports. Even larger additional doses can be expected for reactor operators. These estimations should be mitigated, since increased remote operation (automation, tele-manipulators operation) will be applied in the cycle facilities. At ITU, the new minor actinide laboratory is designed to allow a dose of less than 2 μSv/h to the operators. The real operational dose rate has not yet been determined, but is estimated to be less than is the case when working with glove-boxes in MOX fabrication laboratories. Concerning handling during transport and reactor loading/unloading, some additional doses are unavoidable, but could be limited in their amount by adequate shielding.

Of course, these measures have a direct consequence on the fuel cycle cost, and this is an overall discussion to be held on the cost–benefit ratio of P&T. On the other hand, any additional dose would be better taken into account and treated now than left behind for the concern of future generations.

Conclusions

There is good agreement on the actinide mass inventories from the various codes used by ITU, FZK and CEA for the standard calculation (4·2% enrichment, 50 GWd/t, 6 year cooling). For U and Pu isotopes, agreement is better than 10%; for Am isotopes, agreement is better than $\pm$20%. For ^{242}Cm and ^{244}Cm, agreement is reasonable ($\pm$25%), but less good for ^{245}Cm and ^{246}Cm ($\pm$70%). Since the overall radiotoxicity is dominated by plutonium, the time variation of the radiotoxicities obtained using the various codes is also better than $\pm$10% over the time period 10 to 10^6 years.

This paper has presented a short review of the implications of P&T on the fuel cycle, based on the radiotoxicity of the cycle waste. Two main strategies have been identified.

(*a*) Full multi-recycling of the actinides (Pu, Np, Am and Cm) with high efficiency of P&T processes (99·5% for Pu and 99% for Am + Cm), reducing the radiotoxicity of the spent fuel by more than two orders of magnitude after 500 years (this level of radiotoxicity reduction is reached after 130 000 years in open cycle).
(*b*) Partial multi-recycling which consists of multi-recycling of the Pu and Np (99·5% of P&T overall efficiency), and a single recycle of the Am and Cm in targets in a fast reactor (90% of P&T overall efficiency). With this combination the radiotoxicity of the spent fuel can be reduced by three orders of magnitude after 1500 years. If the Cm is left in the waste, then 3000 years are required to reach the same level of radiotoxicity.

It can be concluded that based on realistic P&T scenarios, the radiotoxicity reduction of the spent fuel of more than two orders of magnitude can be reached after a period of 500–3000 years instead of 130 000 years in open cycle. After these times the residual radiotoxicity is equivalent to 7·83 t of natural uranium (amount of uranium required to produce 1 t of fresh fuel) in equilibrium with its daughter products. It should be noted however that, based on current radiological protection systems, this material would still require isolation from the biosphere.

Appendix. ITU decay calculations

See Tables 3 and 4.

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Table 3. ITU decay results: actinide ingestion radiotoxicities (based on ICRP72) of main components and their daughters

Isotope	Years of cooling														
	10	20	50	100	200	500	1000	2000	5000	10000	20000	50000	100000	200000	500000
^{235}U	$2{\cdot}60 \times 10^{1}$	$2{\cdot}61 \times 10^{1}$	$2{\cdot}66 \times 10^{1}$	$2{\cdot}76 \times 10^{1}$	$3{\cdot}00 \times 10^{1}$	$3{\cdot}66 \times 10^{1}$	$4{\cdot}76 \times 10^{1}$	$6{\cdot}91 \times 10^{1}$	$1{\cdot}31 \times 10^{2}$	$2{\cdot}26 \times 10^{2}$	$3{\cdot}89 \times 10^{2}$	$7{\cdot}13 \times 10^{2}$	$9{\cdot}51 \times 10^{2}$	$1{\cdot}06 \times 10^{3}$	$1{\cdot}08 \times 10^{3}$
^{236}U	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}35 \times 10^{2}$	$6{\cdot}34 \times 10^{2}$	$6{\cdot}34 \times 10^{2}$	$6{\cdot}32 \times 10^{2}$	$6{\cdot}26 \times 10^{2}$
^{238}U	$5{\cdot}56 \times 10^{2}$	$5{\cdot}56 \times 10^{2}$	$5{\cdot}56 \times 10^{2}$	$5{\cdot}56 \times 10^{2}$	$5{\cdot}56 \times 10^{2}$	$5{\cdot}57 \times 10^{2}$	$5{\cdot}58 \times 10^{2}$	$5{\cdot}60 \times 10^{2}$	$5{\cdot}68 \times 10^{2}$	$5{\cdot}95 \times 10^{2}$	$6{\cdot}94 \times 10^{2}$	$1{\cdot}30 \times 10^{3}$	$3{\cdot}03 \times 10^{3}$	$7{\cdot}52 \times 10^{3}$	$1{\cdot}87 \times 10^{4}$
^{237}Np	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}21 \times 10^{3}$	$2{\cdot}27 \times 10^{3}$	$2{\cdot}42 \times 10^{3}$	$2{\cdot}83 \times 10^{3}$	$4{\cdot}25 \times 10^{3}$	$6{\cdot}32 \times 10^{3}$	$9{\cdot}20 \times 10^{3}$	$1{\cdot}23 \times 10^{4}$
^{238}Pu	$4{\cdot}41 \times 10^{7}$	$4{\cdot}07 \times 10^{7}$	$3{\cdot}21 \times 10^{7}$	$2{\cdot}16 \times 10^{7}$	$9{\cdot}37 \times 10^{6}$	$8{\cdot}80 \times 10^{5}$	$2{\cdot}07 \times 10^{4}$	$4{\cdot}51 \times 10^{3}$	$7{\cdot}94 \times 10^{3}$	$1{\cdot}48 \times 10^{4}$	$2{\cdot}79 \times 10^{4}$	$5{\cdot}86 \times 10^{4}$	$8{\cdot}79 \times 10^{4}$	$1{\cdot}01 \times 10^{5}$	$5{\cdot}79 \times 10^{4}$
^{239}Pu	$3{\cdot}36 \times 10^{6}$	$3{\cdot}36 \times 10^{6}$	$3{\cdot}36 \times 10^{6}$	$3{\cdot}35 \times 10^{6}$	$3{\cdot}34 \times 10^{6}$	$3{\cdot}31 \times 10^{6}$	$3{\cdot}27 \times 10^{6}$	$3{\cdot}17 \times 10^{6}$	$2{\cdot}91 \times 10^{6}$	$2{\cdot}52 \times 10^{6}$	$1{\cdot}89 \times 10^{6}$	$8{\cdot}00 \times 10^{5}$	$1{\cdot}91 \times 10^{5}$	$1{\cdot}16 \times 10^{4}$	$9{\cdot}07 \times 10^{2}$
^{240}Pu	$5{\cdot}73 \times 10^{6}$	$5{\cdot}72 \times 10^{6}$	$5{\cdot}70 \times 10^{6}$	$5{\cdot}67 \times 10^{6}$	$5{\cdot}61 \times 10^{6}$	$5{\cdot}43 \times 10^{6}$	$5{\cdot}16 \times 10^{6}$	$4{\cdot}64 \times 10^{6}$	$3{\cdot}38 \times 10^{6}$	$1{\cdot}99 \times 10^{6}$	$6{\cdot}95 \times 10^{5}$	$2{\cdot}96 \times 10^{4}$	$4{\cdot}51 \times 10^{2}$	$3{\cdot}00 \times 10^{2}$	$2{\cdot}98 \times 10^{2}$
^{241}Pu	$2{\cdot}54 \times 10^{7}$	$2{\cdot}82 \times 10^{7}$	$3{\cdot}06 \times 10^{7}$	$2{\cdot}93 \times 10^{7}$	$2{\cdot}48 \times 10^{7}$	$1{\cdot}53 \times 10^{7}$	$6{\cdot}88 \times 10^{6}$	$1{\cdot}39 \times 10^{6}$	$1{\cdot}51 \times 10^{4}$	$4{\cdot}02 \times 10^{3}$	$4{\cdot}70 \times 10^{3}$	$7{\cdot}09 \times 10^{3}$	$1{\cdot}06 \times 10^{4}$	$1{\cdot}54 \times 10^{4}$	$2{\cdot}07 \times 10^{4}$
^{242}Pu	$2{\cdot}99 \times 10^{4}$	$2{\cdot}99 \times 10^{4}$	$2{\cdot}99 \times 10^{4}$	$2{\cdot}99 \times 10^{4}$	$2{\cdot}99 \times 10^{4}$	$2{\cdot}99 \times 10^{4}$	$2{\cdot}99 \times 10^{4}$	$2{\cdot}98 \times 10^{4}$	$2{\cdot}97 \times 10^{4}$	$2{\cdot}94 \times 10^{4}$	$2{\cdot}88 \times 10^{4}$	$2{\cdot}73 \times 10^{4}$	$2{\cdot}49 \times 10^{4}$	$2{\cdot}07 \times 10^{4}$	$1{\cdot}18 \times 10^{4}$
^{241}Am	$1{\cdot}23 \times 10^{7}$	$1{\cdot}21 \times 10^{7}$	$1{\cdot}15 \times 10^{7}$	$1{\cdot}06 \times 10^{7}$	$8{\cdot}98 \times 10^{6}$	$5{\cdot}55 \times 10^{6}$	$2{\cdot}49 \times 10^{6}$	$5{\cdot}03 \times 10^{5}$	$5{\cdot}51 \times 10^{3}$	$1{\cdot}51 \times 10^{3}$	$1{\cdot}76 \times 10^{3}$	$2{\cdot}66 \times 10^{3}$	$3{\cdot}96 \times 10^{3}$	$5{\cdot}78 \times 10^{3}$	$7{\cdot}75 \times 10^{3}$
^{242m}Am	$9{\cdot}05 \times 10^{4}$	$9{\cdot}23 \times 10^{4}$	$9{\cdot}46 \times 10^{4}$	$9{\cdot}13 \times 10^{4}$	$7{\cdot}16 \times 10^{4}$	$2{\cdot}27 \times 10^{4}$	$2{\cdot}26 \times 10^{5}$	$3{\cdot}71 \times 10^{1}$	$3{\cdot}01 \times 10^{1}$	$5{\cdot}05 \times 10^{1}$	$8{\cdot}99 \times 10^{1}$	$1{\cdot}82 \times 10^{2}$	$2{\cdot}70 \times 10^{2}$	$3{\cdot}10 \times 10^{2}$	$1{\cdot}77 \times 10^{2}$
^{243}Am	$3{\cdot}13 \times 10^{5}$	$3{\cdot}13 \times 10^{5}$	$3{\cdot}12 \times 10^{5}$	$3{\cdot}11 \times 10^{5}$	$3{\cdot}09 \times 10^{5}$	$3{\cdot}04 \times 10^{5}$	$2{\cdot}95 \times 10^{5}$	$2{\cdot}79 \times 10^{5}$	$2{\cdot}37 \times 10^{5}$	$1{\cdot}84 \times 10^{5}$	$1{\cdot}18 \times 10^{5}$	$4{\cdot}21 \times 10^{4}$	$9{\cdot}73 \times 10^{3}$	$5{\cdot}78 \times 10^{2}$	$3{\cdot}22 \times 10^{1}$
^{242}Cm	$7{\cdot}08 \times 10^{2}$	$6{\cdot}42 \times 10^{2}$	$5{\cdot}07 \times 10^{2}$	$3{\cdot}41 \times 10^{2}$	$1{\cdot}48 \times 10^{2}$	$1{\cdot}39 \times 10^{1}$	$3{\cdot}26 \times 10^{-1}$	$7{\cdot}07 \times 10^{-2}$	$1{\cdot}25 \times 10^{-1}$	$2{\cdot}32 \times 10^{-1}$	$4{\cdot}38 \times 10^{-1}$	$9{\cdot}19 \times 10^{-1}$	$1{\cdot}38 \times 10^{0}$	$1{\cdot}59 \times 10^{0}$	$9{\cdot}09 \times 10^{-1}$
^{243}Cm	$2{\cdot}09 \times 10^{5}$	$1{\cdot}65 \times 10^{5}$	$8{\cdot}11 \times 10^{4}$	$2{\cdot}50 \times 10^{4}$	$2{\cdot}43 \times 10^{3}$	$4{\cdot}57 \times 10^{2}$	$4{\cdot}49 \times 10^{2}$	$4{\cdot}37 \times 10^{2}$	$4{\cdot}01 \times 10^{2}$	$3{\cdot}47 \times 10^{2}$	$2{\cdot}60 \times 10^{2}$	$1{\cdot}10 \times 10^{2}$	$2{\cdot}62 \times 10^{1}$	$1{\cdot}60 \times 10^{0}$	$1{\cdot}25 \times 10^{-1}$
^{244}Cm	$2{\cdot}41 \times 10^{7}$	$1{\cdot}65 \times 10^{7}$	$5{\cdot}33 \times 10^{6}$	$9{\cdot}23 \times 10^{5}$	$1{\cdot}71 \times 10^{5}$	$1{\cdot}53 \times 10^{5}$	$1{\cdot}45 \times 10^{5}$	$1{\cdot}31 \times 10^{5}$	$9{\cdot}53 \times 10^{4}$	$5{\cdot}62 \times 10^{4}$	$1{\cdot}96 \times 10^{4}$	$8{\cdot}34 \times 10^{2}$	$1{\cdot}27 \times 10^{1}$	$8{\cdot}44 \times 10^{0}$	$8{\cdot}37 \times 10^{0}$
^{245}Cm	$5{\cdot}76 \times 10^{3}$	$5{\cdot}83 \times 10^{3}$	$6{\cdot}05 \times 10^{3}$	$6{\cdot}42 \times 10^{3}$	$7{\cdot}12 \times 10^{3}$	$8{\cdot}49 \times 10^{3}$	$9{\cdot}52 \times 10^{3}$	$9{\cdot}64 \times 10^{3}$	$7{\cdot}74 \times 10^{3}$	$5{\cdot}15 \times 10^{3}$	$2{\cdot}29 \times 10^{3}$	$2{\cdot}17 \times 10^{2}$	$3{\cdot}52 \times 10^{1}$	$4{\cdot}86 \times 10^{1}$	$6{\cdot}71 \times 10^{1}$
^{246}Cm	$1{\cdot}62 \times 10^{3}$	$1{\cdot}61 \times 10^{3}$	$1{\cdot}61 \times 10^{3}$	$1{\cdot}60 \times 10^{3}$	$1{\cdot}57 \times 10^{3}$	$1{\cdot}51 \times 10^{3}$	$1{\cdot}40 \times 10^{3}$	$1{\cdot}21 \times 10^{3}$	$7{\cdot}90 \times 10^{2}$	$3{\cdot}92 \times 10^{2}$	$1{\cdot}08 \times 10^{2}$	$2{\cdot}27 \times 10^{1}$	$1{\cdot}97 \times 10^{1}$	$1{\cdot}64 \times 10^{1}$	$9{\cdot}39 \times 10^{0}$
U	$1{\cdot}22 \times 10^{3}$	$1{\cdot}22 \times 10^{3}$	$1{\cdot}22 \times 10^{3}$	$1{\cdot}22 \times 10^{3}$	$1{\cdot}22 \times 10^{3}$	$1{\cdot}23 \times 10^{3}$	$1{\cdot}24 \times 10^{3}$	$1{\cdot}26 \times 10^{3}$	$1{\cdot}33 \times 10^{3}$	$1{\cdot}46 \times 10^{3}$	$1{\cdot}72 \times 10^{3}$	$2{\cdot}65 \times 10^{3}$	$4{\cdot}61 \times 10^{3}$	$9{\cdot}22 \times 10^{3}$	$2{\cdot}04 \times 10^{4}$
Np	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}20 \times 10^{3}$	$2{\cdot}21 \times 10^{3}$	$2{\cdot}27 \times 10^{3}$	$2{\cdot}42 \times 10^{3}$	$2{\cdot}83 \times 10^{3}$	$4{\cdot}25 \times 10^{3}$	$6{\cdot}32 \times 10^{3}$	$9{\cdot}20 \times 10^{3}$	$1{\cdot}23 \times 10^{4}$
Pu	$7{\cdot}86 \times 10^{7}$	$7{\cdot}80 \times 10^{7}$	$7{\cdot}18 \times 10^{7}$	$6{\cdot}00 \times 10^{7}$	$4{\cdot}31 \times 10^{7}$	$2{\cdot}50 \times 10^{7}$	$1{\cdot}54 \times 10^{7}$	$9{\cdot}24 \times 10^{6}$	$6{\cdot}35 \times 10^{6}$	$4{\cdot}57 \times 10^{6}$	$2{\cdot}65 \times 10^{6}$	$9{\cdot}22 \times 10^{5}$	$3{\cdot}15 \times 10^{5}$	$1{\cdot}49 \times 10^{5}$	$9{\cdot}16 \times 10^{4}$
Am	$1{\cdot}27 \times 10^{7}$	$1{\cdot}25 \times 10^{7}$	$1{\cdot}19 \times 10^{7}$	$1{\cdot}10 \times 10^{7}$	$9{\cdot}36 \times 10^{6}$	$5{\cdot}88 \times 10^{6}$	$3{\cdot}01 \times 10^{6}$	$7{\cdot}82 \times 10^{5}$	$2{\cdot}42 \times 10^{5}$	$1{\cdot}85 \times 10^{5}$	$1{\cdot}20 \times 10^{5}$	$4{\cdot}49 \times 10^{4}$	$1{\cdot}40 \times 10^{4}$	$6{\cdot}67 \times 10^{3}$	$7{\cdot}96 \times 10^{3}$
Cm	$2{\cdot}43 \times 10^{7}$	$1{\cdot}66 \times 10^{7}$	$5{\cdot}42 \times 10^{6}$	$9{\cdot}57 \times 10^{5}$	$1{\cdot}83 \times 10^{5}$	$1{\cdot}64 \times 10^{5}$	$1{\cdot}57 \times 10^{5}$	$1{\cdot}42 \times 10^{5}$	$1{\cdot}04 \times 10^{5}$	$6{\cdot}21 \times 10^{4}$	$2{\cdot}22 \times 10^{4}$	$1{\cdot}18 \times 10^{3}$	$9{\cdot}52 \times 10^{1}$	$7{\cdot}66 \times 10^{1}$	$8{\cdot}59 \times 10^{1}$
Total	$1{\cdot}16 \times 10^{8}$	$1{\cdot}07 \times 10^{8}$	$8{\cdot}92 \times 10^{7}$	$7{\cdot}20 \times 10^{7}$	$5{\cdot}27 \times 10^{7}$	$3{\cdot}10 \times 10^{7}$	$1{\cdot}85 \times 10^{7}$	$1{\cdot}02 \times 10^{7}$	$6{\cdot}70 \times 10^{6}$	$4{\cdot}82 \times 10^{6}$	$2{\cdot}80 \times 10^{6}$	$9{\cdot}75 \times 10^{5}$	$3{\cdot}39 \times 10^{5}$	$1{\cdot}75 \times 10^{5}$	$1{\cdot}32 \times 10^{5}$

Reference radiotoxicity level of $2{\cdot}41 \times 10^{5}$ Sv reached after 127500 years.

Table 4. ITU decay results: fission product ingestion radiotoxicities (based on ICRP72) of main components and their daughters

	Masses (ITU)	Years of cooling													
		10	20	50	100	200	500	1000	2000	5000	10000	20000	50000	100000	200000	500000
^{10}Be	$1{\cdot}96\times10^{-4}$	$1{\cdot}89\times10^{-4}$	$1{\cdot}89\times10^{-4}$	$1{\cdot}89\times10^{-4}$	$1{\cdot}89\times10^{-4}$	$1{\cdot}89\times10^{-4}$	$1{\cdot}89\times10^{-4}$	$1{\cdot}89\times10^{-4}$	$1{\cdot}88\times10^{-4}$	$1{\cdot}88\times10^{-4}$	$1{\cdot}88\times10^{-4}$	$1{\cdot}87\times10^{-4}$	$1{\cdot}84\times10^{-4}$	$1{\cdot}80\times10^{-4}$	$1{\cdot}72\times10^{-4}$	$1{\cdot}50\times10^{-4}$
^{14}C	$3{\cdot}96\times10^{-5}$	$3{\cdot}78\times10^{-3}$	$3{\cdot}78\times10^{-3}$	$3{\cdot}77\times10^{-3}$	$3{\cdot}74\times10^{-3}$	$3{\cdot}69\times10^{-3}$	$3{\cdot}56\times10^{-3}$	$3{\cdot}35\times10^{-3}$	$2{\cdot}97\times10^{-3}$	$2{\cdot}07\times10^{-3}$	$1{\cdot}13\times10^{-3}$	$3{\cdot}37\times10^{-4}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{79}Se	$8{\cdot}75\times10^{0}$	$6{\cdot}54\times10^{0}$	$6{\cdot}54\times10^{0}$	$6{\cdot}54\times10^{0}$	$6{\cdot}54\times10^{0}$	$6{\cdot}54\times10^{0}$	$6{\cdot}54\times10^{0}$	$6{\cdot}54\times10^{0}$	$6{\cdot}53\times10^{0}$	$6{\cdot}51\times10^{0}$	$6{\cdot}47\times10^{0}$	$6{\cdot}41\times10^{0}$	$6{\cdot}20\times10^{0}$	$5{\cdot}88\times10^{0}$	$5{\cdot}29\times10^{0}$	$3{\cdot}84\times10^{0}$
^{81}Kr	$4{\cdot}26\times10^{-5}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{87}Rb	$3{\cdot}59\times10^{2}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$	$1{\cdot}73\times10^{-3}$
^{93}Zr	$1{\cdot}06\times10^{3}$	$1{\cdot}27\times10^{1}$	$1{\cdot}62\times10^{1}$	$2{\cdot}09\times10^{1}$	$2{\cdot}25\times10^{1}$	$2{\cdot}27\times10^{1}$	$2{\cdot}27\times10^{1}$	$2{\cdot}27\times10^{1}$	$2{\cdot}27\times10^{1}$	$2{\cdot}26\times10^{1}$	$2{\cdot}26\times10^{1}$	$2{\cdot}25\times10^{1}$	$2{\cdot}22\times10^{1}$	$2{\cdot}17\times10^{1}$	$2{\cdot}07\times10^{1}$	$1{\cdot}81\times10^{1}$
^{94}Nb	$1{\cdot}15\times10^{-3}$	$1{\cdot}36\times10^{-2}$	$1{\cdot}36\times10^{-2}$	$1{\cdot}35\times10^{-2}$	$1{\cdot}35\times10^{-2}$	$1{\cdot}35\times10^{-2}$	$1{\cdot}33\times10^{-2}$	$1{\cdot}31\times10^{-2}$	$1{\cdot}27\times10^{-2}$	$1{\cdot}14\times10^{-2}$	$9{\cdot}64\times10^{-3}$	$6{\cdot}86\times10^{-3}$	$2{\cdot}46\times10^{-3}$	$4{\cdot}47\times10^{-4}$	$1{\cdot}47\times10^{-5}$	$0{\cdot}00\times10^{0}$
^{98}Tc	$1{\cdot}37\times10^{-2}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$	$1{\cdot}10\times10^{-3}$
^{99}Tc	$1{\cdot}09\times10^{3}$	$5{\cdot}66\times10^{2}$	$5{\cdot}66\times10^{2}$	$5{\cdot}66\times10^{2}$	$5{\cdot}66\times10^{2}$	$5{\cdot}66\times10^{2}$	$5{\cdot}65\times10^{2}$	$5{\cdot}64\times10^{2}$	$5{\cdot}63\times10^{2}$	$5{\cdot}57\times10^{2}$	$5{\cdot}48\times10^{2}$	$5{\cdot}30\times10^{2}$	$4{\cdot}81\times10^{2}$	$4{\cdot}08\times10^{2}$	$2{\cdot}94\times10^{2}$	$1{\cdot}10\times10^{2}$
^{107}Pd	$3{\cdot}53\times10^{2}$	$2{\cdot}49\times10^{-1}$	$2{\cdot}49\times10^{-1}$	$2{\cdot}49\times10^{-1}$	$2{\cdot}49\times10^{-1}$	$2{\cdot}49\times10^{-1}$	$2{\cdot}49\times10^{-1}$	$2{\cdot}49\times10^{-1}$	$2{\cdot}49\times10^{-1}$	$2{\cdot}48\times10^{-1}$	$2{\cdot}48\times10^{-1}$	$2{\cdot}48\times10^{-1}$	$2{\cdot}47\times10^{-1}$	$2{\cdot}46\times10^{-1}$	$2{\cdot}43\times10^{-1}$	$2{\cdot}36\times10^{-1}$
^{108m}Ag	$1{\cdot}81\times10^{-6}$	$1{\cdot}21\times10^{-3}$	$1{\cdot}19\times10^{-3}$	$1{\cdot}14\times10^{-3}$	$1{\cdot}04\times10^{-3}$	$8{\cdot}76\times10^{-4}$	$5{\cdot}33\times10^{-4}$	$2{\cdot}33\times10^{-4}$	$4{\cdot}44\times10^{-5}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{115}In	$2{\cdot}56\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{121m}Sn	$5{\cdot}05\times10^{-3}$	$5{\cdot}33\times10^{0}$	$4{\cdot}70\times10^{0}$	$3{\cdot}22\times10^{0}$	$1{\cdot}72\times10^{0}$	$4{\cdot}52\times10^{-1}$	$1{\cdot}03\times10^{-2}$	$1{\cdot}90\times10^{-5}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{126}Sn	$4{\cdot}14\times10^{1}$	$1{\cdot}07\times10^{2}$	$1{\cdot}07\times10^{2}$	$1{\cdot}07\times10^{2}$	$1{\cdot}07\times10^{2}$	$1{\cdot}07\times10^{2}$	$1{\cdot}06\times10^{2}$	$1{\cdot}06\times10^{2}$	$1{\cdot}06\times10^{2}$	$1{\cdot}05\times10^{2}$	$1{\cdot}03\times10^{2}$	$9{\cdot}97\times10^{1}$	$9{\cdot}02\times10^{1}$	$7{\cdot}63\times10^{1}$	$5{\cdot}46\times10^{1}$	$2{\cdot}00\times10^{1}$
^{123}Te	$2{\cdot}07\times10^{-2}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{129}I	$2{\cdot}67\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}92\times10^{2}$	$1{\cdot}91\times10^{2}$	$1{\cdot}90\times10^{2}$	$1{\cdot}88\times10^{2}$
^{135}Cs	$5{\cdot}39\times10^{2}$	$4{\cdot}60\times10^{1}$	$4{\cdot}60\times10^{1}$	$4{\cdot}60\times10^{1}$	$4{\cdot}60\times10^{1}$	$4{\cdot}60\times10^{1}$	$4{\cdot}59\times10^{1}$	$4{\cdot}59\times10^{1}$	$4{\cdot}59\times10^{1}$	$4{\cdot}59\times10^{1}$	$4{\cdot}58\times10^{1}$	$4{\cdot}57\times10^{1}$	$4{\cdot}53\times10^{1}$	$4{\cdot}46\times10^{1}$	$4{\cdot}33\times10^{1}$	$3{\cdot}95\times10^{1}$
^{138}La	$1{\cdot}41\times10^{-1}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{146}Sm	$1{\cdot}42\times10^{-2}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$	$6{\cdot}75\times10^{-4}$
^{147}Sm	$2{\cdot}00\times10^{2}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$	$8{\cdot}32\times10^{-3}$
^{151}Sm	$1{\cdot}82\times10^{1}$	$1{\cdot}68\times10^{3}$	$1{\cdot}56\times10^{3}$	$1{\cdot}24\times10^{3}$	$8{\cdot}43\times10^{2}$	$3{\cdot}73\times10^{2}$	$3{\cdot}70\times10^{1}$	$7{\cdot}89\times10^{-1}$	$3{\cdot}59\times10^{-4}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{3}H	$6{\cdot}07\times10^{-2}$	$3{\cdot}10\times10^{2}$	$1{\cdot}77\times10^{2}$	$3{\cdot}28\times10^{1}$	$1{\cdot}98\times10^{0}$	$5{\cdot}13\times10^{-3}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{85}Kr	$2{\cdot}33\times10^{1}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$6{\cdot}42\times10^{2}$	$3{\cdot}91\times10^{-3}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{90}Sr	$6{\cdot}73\times10^{2}$	$9{\cdot}57\times10^{7}$	$7{\cdot}53\times10^{7}$	$3{\cdot}66\times10^{7}$	$1{\cdot}10\times10^{7}$	$8{\cdot}64\times10^{5}$	$5{\cdot}84\times10^{-4}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{93m}Nb	$2{\cdot}96\times10^{-3}$	$2{\cdot}64\times10^{0}$	$1{\cdot}72\times10^{0}$	$4{\cdot}74\times10^{-1}$	$5{\cdot}54\times10^{-2}$	$5{\cdot}84\times10^{-4}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{106}Ru	$3{\cdot}72\times10^{0}$	$2{\cdot}12\times10^{5}$	$2{\cdot}43\times10^{2}$	$3{\cdot}64\times10^{-7}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{110m}Ag	$3{\cdot}82\times10^{-3}$	$3{\cdot}27\times10^{1}$	$1{\cdot}31\times10^{-3}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{109}Cd	$5{\cdot}20\times10^{-8}$	$1{\cdot}12\times10^{-3}$	$4{\cdot}72\times10^{-6}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{113m}Cd	$3{\cdot}31\times10^{-1}$	$5{\cdot}20\times10^{4}$	$3{\cdot}18\times10^{4}$	$7{\cdot}28\times10^{3}$	$6{\cdot}25\times10^{2}$	$3{\cdot}42\times10^{0}$	$1{\cdot}36\times10^{-6}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{119m}Sn	$1{\cdot}43\times10^{-4}$	$2{\cdot}13\times10^{-1}$	$3{\cdot}81\times10^{-5}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{125}Sb	$4{\cdot}36\times10^{0}$	$1{\cdot}24\times10^{5}$	$1{\cdot}01\times10^{4}$	$5{\cdot}38\times10^{0}$	$1{\cdot}89\times10^{-5}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{134}Cs	$3{\cdot}09\times10^{1}$	$7{\cdot}34\times10^{6}$	$2{\cdot}25\times10^{5}$	$1{\cdot}09\times10^{1}$	$5{\cdot}67\times10^{-7}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{137}Cs	$1{\cdot}56\times10^{3}$	$5{\cdot}94\times10^{7}$	$4{\cdot}72\times10^{7}$	$2{\cdot}36\times10^{7}$	$7{\cdot}47\times10^{6}$	$6{\cdot}50\times10^{5}$	$6{\cdot}49\times10^{2}$	$6{\cdot}45\times10^{-3}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{144}Ce	$2{\cdot}06\times10^{0}$	$3{\cdot}65\times10^{4}$	$5{\cdot}08\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
^{147}Pm	$3{\cdot}06\times10^{1}$	$9{\cdot}50\times10^{4}$	$6{\cdot}77\times10^{3}$	$2{\cdot}46\times10^{0}$	$1{\cdot}28\times10^{-3}$	$1{\cdot}27\times10^{-3}$	$1{\cdot}27\times10^{-3}$	$1{\cdot}27\times10^{-3}$	$1{\cdot}27\times10^{-3}$	$1{\cdot}27\times10^{-3}$						
Short FPs		$1{\cdot}63\times10^{8}$	$1{\cdot}23\times10^{8}$	$6{\cdot}03\times10^{7}$	$1{\cdot}85\times10^{7}$	$1{\cdot}51\times10^{6}$	$1{\cdot}29\times10^{3}$	$1{\cdot}16\times10^{-2}$	$1{\cdot}27\times10^{-3}$	$1{\cdot}27\times10^{-3}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$	$0{\cdot}00\times10^{0}$
Long FPs		$2{\cdot}62\times10^{3}$	$2{\cdot}50\times10^{3}$	$2{\cdot}18\times10^{3}$	$1{\cdot}78\times10^{3}$	$1{\cdot}31\times10^{3}$	$9{\cdot}76\times10^{2}$	$9{\cdot}39\times10^{2}$	$9{\cdot}36\times10^{2}$	$9{\cdot}29\times10^{2}$	$9{\cdot}18\times10^{2}$	$8{\cdot}97\times10^{2}$	$8{\cdot}36\times10^{2}$	$7{\cdot}48\times10^{2}$	$6{\cdot}08\times10^{2}$	$3{\cdot}79\times10^{2}$
All FPs		$1{\cdot}63\times10^{8}$	$1{\cdot}23\times10^{8}$	$6{\cdot}03\times10^{7}$	$1{\cdot}85\times10^{7}$	$1{\cdot}52\times10^{6}$	$2{\cdot}27\times10^{3}$	$9{\cdot}39\times10^{2}$	$9{\cdot}36\times10^{2}$	$9{\cdot}29\times10^{2}$	$9{\cdot}18\times10^{2}$	$8{\cdot}97\times10^{2}$	$8{\cdot}36\times10^{2}$	$7{\cdot}48\times10^{2}$	$6{\cdot}08\times10^{2}$	$3{\cdot}79\times10^{2}$

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