TRANSMUTATION OF TC-99 IN FISSION REACTORS

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Abstract
Transmutation of Tc-99 in three different types of fission reactors is considered: a heavy water reactor, a fast reactor and a light water reactor. For the first type a CANDU reactor was chosen, for the second one the Superphénix reactor, and for the third one a PWR. The three most promising Tc-99 transmuters are the fast reactor with a moderated subassembly in the inner core, a fast reactor with a non-moderated subassembly in the inner core, and a heavy water reactor with Tc-99 target pins in the moderator between the fuel bundles. Transmutation half lives of 15 to 25 years can be achieved, with yearly transmuted Tc-99 masses of about 100 kg at a thermal reactor power of about 3000 MW.

1 Introduction

The radiotoxicity of fission products after a storage time of several thousands of years is mainly determined by only three isotopes: I-129, Tc-99 and Cs-135. Although the radiotoxicity of fission products is not significant compared with the radiotoxicity of actinides in spent fuel, the importance of fission products becomes apparent when the solubility of fission products is taken into account (sometimes called 'mobility'). Studies on storage of vitrified waste in salt layers [1] show that dose rates after about one to two millions of years are dominated by the neptunium decay chain and by fission products (Cs-135 and I-129). Studies on storage of spent fuel and vitrified waste in granite [2] also show that the dominating nuclides are Tc-99 and the neptunium decay chain.

This paper deals only with transmutation of Tc-99, which may be accomplished by a single neutron capture. Because no neutrons are produced in the transmutation process, the introduction of Tc-99 in a reactor will always lead to a reactivity decrease, which can be compensated by an increased fuel enrichment. The cross section of Tc-99 is rather low (see Figure 1.1), both in the thermal and in the fast energy range. This means that a high thermal or fast neutron flux is needed to achieve acceptably low transmutation half lives (see chapter 2). This report ranks fission reactors with respect to their Tc-99 transmutation capability.

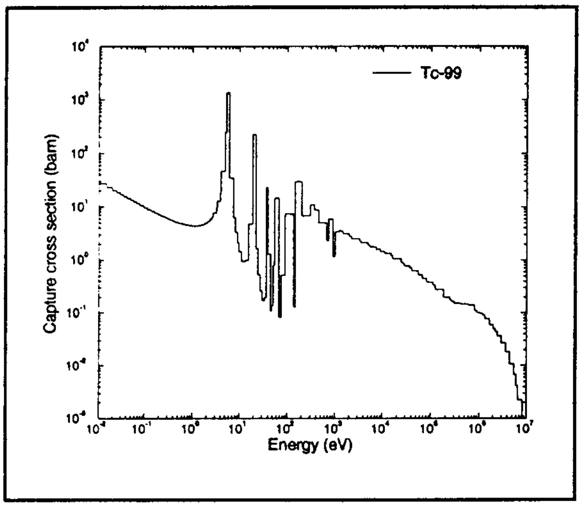

Fig 1.1: *Capture cross section of Tc-99 as function of energy.*

2 Transmutation in Heavy Water Reactors

Introduction

The transmutation rate of Tc-99 depends on both the neutron spectrum and the flux level. A reactor with a relatively high flux and a soft neutron spectrum could be a very good Tc-99 transmuter, as softening the neutron spectrum by a moderator will usually lead to higher spectrum-averaged cross sections. A high thermal neutron flux and a soft neutron spectrum are typical for a Heavy Water Reactor (HWR) like CANDU. The use of deuterium as moderator instead of hydrogen leads to very low neutron absorption in the moderator, while the use of natural uranium as fuel leads to low thermal absorption cross sections in the fuel and as a consequence a high thermal neutron flux at achievable power rating. Although the introduction of Tc-99 in the core of a HWR will most probably change these characteristics, it seems worthwile to investigate the possibilities of a HWR as Tc-99 transmuter.

Model

Data mentioned in this chapter have been taken from the CANDU type HWR as present in Darlington (Can) with a power of 935 MWe. The geometry of a standard fuel bundle is shown in Figure 2.1. Along the line from the centre fuel pin (the "first" ring of fuel pins) to the moderator, the second, third and fourth ring of fuel pins are shown with the pressure tube, the gas annulus, the calandria tube and the moderator. The gas annulus between the pressure tube and the calandria tube is filled with gas to limit heat transfer from the fuel bundle to the moderator. All fuel bundles for a given reactor design are equal.

Four cases were considered, all with equal amount of Tc-99 per fuel bundle. Case HWR-A corresponds with the centre fuel pin of each fuel bundle exchanged for a Tc-99 pin. This is shown in Figure 2.2, where the black pin in the centre stands for the Tc-99 pin. Case HWR-B corresponds with nine fuel pins in the outer ring of a fuel bundle exchanged for Tc-99 pins. This fuel bundle is then surrounded by eight fuel bundles without Tc-99. This is shown in Figure 2.3. Case HWR-C corresponds with Tc-99 pins positioned in the moderator between the fuel bundles. This is shown in Figure 2.4. Case HWR-D corresponds with Tc-99 homogeneously dissolved in the moderator between the fuel bundles. The four cases are summarized in Table 2.1.

Table 2.1: *Transmutation cases for the HWR. All cases contain an equal amount of Tc-99.*

Case	Description
HWR-A	Tc-99 target pin in the centre of each fuel bundle.
HWR-B	Nine Tc-99 target pins in the outer fuel ring of one fuel bundle surrounded by eight standard fuel bundles.
HWR-C	Tc-99 target pins in the moderator between fuel bundles.
HWR-D	Tc-99 homogeneously dissolved in the moderator.

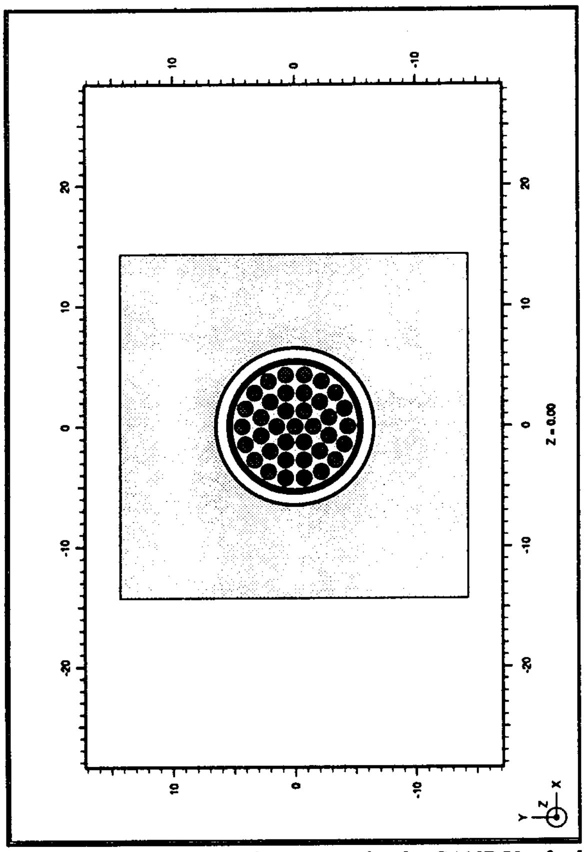

Fig 2.1: *Geometry of a standard CANDU fuel bundle.*

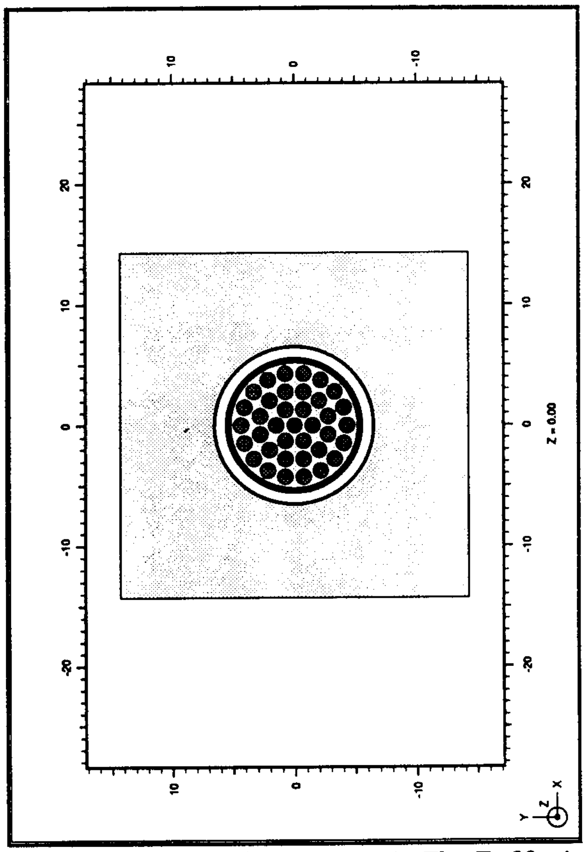

Fig 2.2: *Geometry of case HWR-A. The Tc-99 pin is located at the centre of the fuel bundle.*

All calculations were done with the KENO Monte Carlo code [3]. The transmutation half life was calculated from:

$$T_{1/2}=\frac{\ln 2}{\sigma\phi} \qquad (1)$$

where $T_{1/2}$ is the transmutation half life, σ is the one-group capture cross section of Tc-99 and ϕ is the neutron flux. All data libraries used were based on the JEF2.2 library.

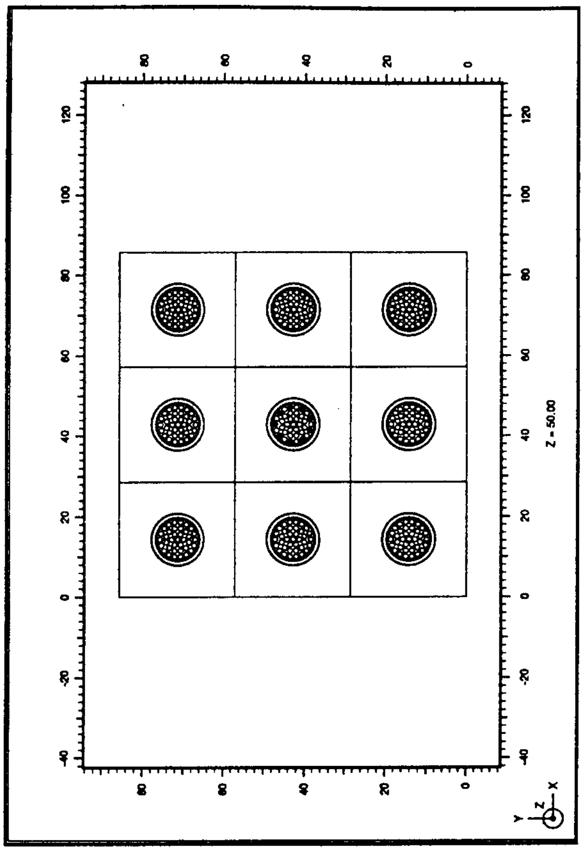

Fig 2.3: *Geometry of case HWR-B. Nine Tc-99 pins are located in the outer ring of the centre fuel bundle.*

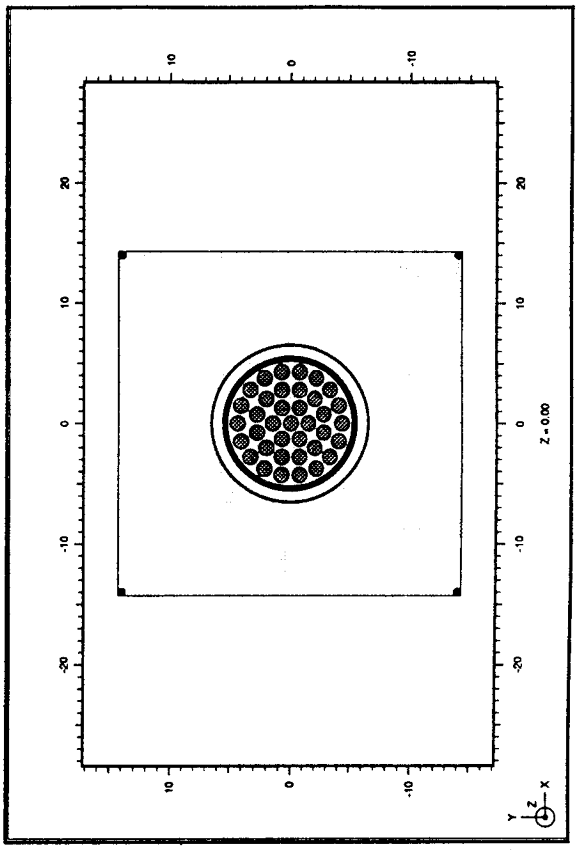

Fig 2.4: *Geometry of case HWR-C. The Tc-99 pins are located in the moderator between the fuel bundles (in the corners of the figure).*

Results

Results of the calculations are given in Table 2.2. It is seen that the transmutation half lives range from about 44 years for case HWR-A to 11 years for case HWR-D. This last case is however quite unrealistic, because it is assumed here that only the moderator between the fuel channels contains Tc-99. In reality the moderator volume is much larger, which implies that a large part of the Tc-99 is contained outside the core region. The neutron flux outside the core is very low. When the moderator regions inside and outside the core cannot be separated, the results of this case will be much worse. The loaded Tc-99 mass in all cases equals about 4.1 tonnes, which is quite high.

Table 2.2: *Results for transmutation of Tc-99 in HWRs. The Tc-99 loading in all cases is 4.1 tonnes. The HWR reference design uses natural uranium as fuel.*

Case	Enrichment (^{w}%)	Neutron flux ($cm^{-2}s^{-1}$)	Tc-99 cross section (barn)	Transm rate (kg/a)	Half life (a)
HWR-A	0.94	$1.51\ 10^{14}$	3.29	65	44.2
HWR-B	0.95	$9.07\ 10^{13}$	6.01	70	40.3
HWR-C	1.30	$9.07\ 10^{13}$	9.89	115	24.5
HWR-D	3.20	$1.36\ 10^{14}$	14.6	252	11.0

Conclusions for the HWR
The results of this chapter show that transmutation of Tc-99 in HWRs is feasible. When one fuel pin per fuel bundle is exchanged for a Tc-99 pin (cases HWR-A and HWR-B), a gross yearly transmutation rate of about 65 kg is obtained, which is the yearly production of about three 1000 MWe LWRs. More promising is case HWR-C, where Tc-99 pins are put in the moderator between the fuel bundles. This seems practically achievable. The yearly Tc-99 production in the HWR itself equals about 25 kg. This amount is not yet subtracted.

3 Transmutation in Fast Reactors

Introduction
Transmutation of Tc-99 may be accomplished in a Fast Reactor (FR) in three ways. In a special moderated subassembly (a subassembly with pins containing moderator) loaded at the periphery of the core, in a special moderated subassembly loaded in the inner core, and in a special non-moderated subassembly loaded in the inner core. The first option has been described in reference 4. Transmutation of Tc-99 in the periphery of a fast reactor core with thermal power of 2600 MW leads to transmutation half lives of 40 to 50 years with yearly transmuted Tc-99 masses of 60 to 70 kg. The Tc-99 loading in such cases equals about 4.7 tonnes of Tc-99. Reducing the Tc-99 inventory to about 500 kg leads to lower transmutation half lives of about 15 years due to reduced self shielding. The yearly transmuted Tc-99 mass is reduced then to about 20 to 25 kg, which is only just enough to compensate for the reactors own Tc-99 production. Generally transmutation efficiencies of this scheme are only moderate.
The second method for transmutation of Tc-99 in fast reactors has been considered in this chapter because of its promises of shorter half lives and larger amounts of Tc-99 yearly transmuted. Values for the transmutation half life of 17 years with yearly transmuted Tc-99 mass of 96 kg are quoted in reference 5. The thermal neutron flux in a moderated subassembly in the inner core of a fast reactor is expected to be quite high, of the order of 10^{14} to 10^{15} $cm^{-2}s^{-1}$. Moderation cannot be accomplished by water because of the presence of sodium in the core, therefore CaH_2 with density of 1.5 g cm^{-3} has been used. Besides the transmutation ratė of Tc-99, the needed fuel enrichment and the power peaking in nearby fuel pins caused by moderation in the special subassembly are important.
Although fast neutron cross sections of Tc-99 are relatively low, transmutation of Tc-99 in a fast reactor without moderation could be advantageous because of its very high fast neutron flux and beause of the lack of power peaking and other side effects. This option has also been considered in this chapter.

Model
The Superhénix reactor with a thermal power of 3000 MW was used as a base design for the calculations. A geometric model was built consisting of fuel pins, Tc-99 pins and moderator pins (pins containing CaH_2), all with same diameter. The Tc-99 loading is characterized by the ratio of the number of fuel pins and Tc-99 pins. The void in the fuel pin was smeared with the fuel; structural materials were smeared with the coolant.
All calculations were done with the Monte Carlo code KENO [3] with data libraries based on JEF2.2. Because no burnup calculations can be done with the Monte Carlo code KENO, the transmutation half life was calculated according to equation 1.

Results for a moderated subassembly in the inner core

The Tc-99 transmutation half life was calculated for several cases with varying ratio of Tc-99 and moderator, accomplished by replacing moderator pins in the moderated subassembly by Tc-99 pins. The number of Tc-99 and moderator pins always summed to 271, which is the number of pins per assembly. The number of fuel pins for all cases in this paragraph was equal to 1098, which corresponds to slightly more than four fuel assemblies. Because the inner core of the Superphénix reactor contains 193 assemblies, which equals 52303 fuel pins, the modelled section represents 2.62% of the inner core, or 1.39% of the inner and outer core.

Case FR-A corresponds to the case where the outer three layers of pins in the moderated subassembly are occupied with Tc-99 pins, and all inner layers in the moderated subassembly are occupied with moderator pins. This configuration is shown in Figure 3.1. Cases FR-B to FR-H correspond to one more layer of Tc-99 pins each case. This means that for case FR-H all moderator pins are replaced by Tc-99 pins. This configuration is shown in Figure 3.2. Results for all these cases are given in Table 3.1. The enrichment shown in the table is that enrichment needed to get the k_∞ of standard fuel at BOC (about 1.17). The flux is normalised such that the average specific power is 114 W g^{-1} fuel. It should be noted that the fuel enrichment for cases FR-A to FR-F exceed 30^{w}%, which is considered as an upper limit. This means that cases FR-A to FR-F are most probably not practically achievable and that the number of moderated subassemblies in the core has to be decreased to get a lower Tc-99 loading and a lower fuel enrichment requirement.

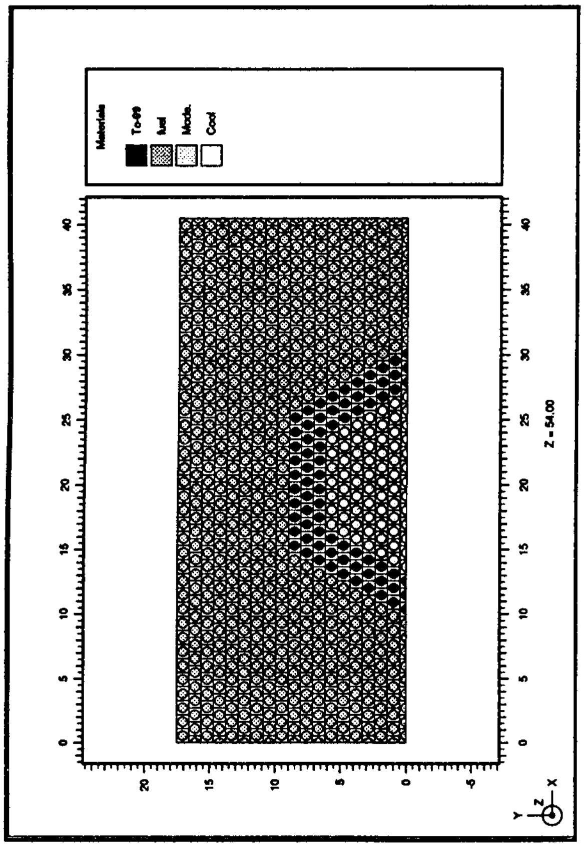

Fig 3.1: *Geometry for case FR-A. The fuel pins are located outside, the moderator pins inside the special subassembly.*

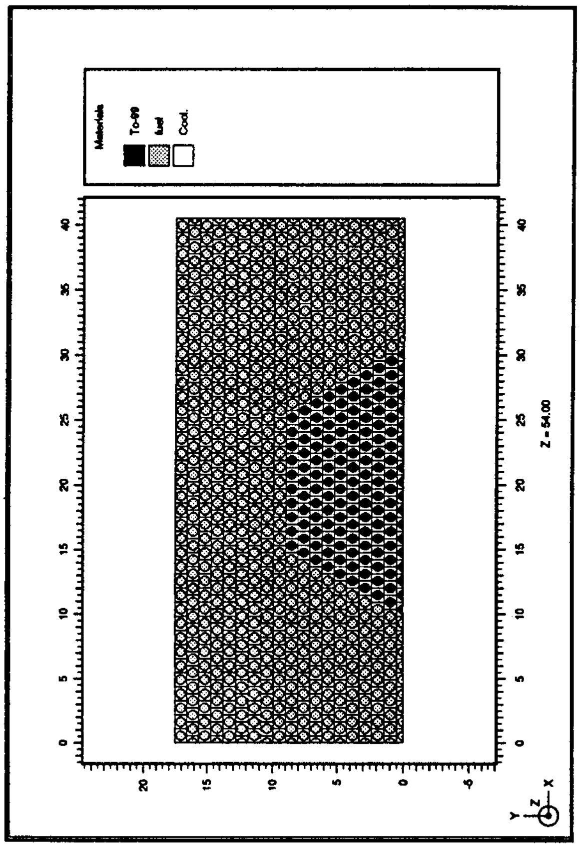

Fig 3.2: *Configuration for case FR-H. In this case no moderator pins are present.*

Due to the moderator in the special subassembly, the power in the fuel pins adjacent to the special subassembly increases with 30% for case FR-A, 12% for case FR-B and only 1% for case FR-C. With increasing number of Tc-99 pins in the special moderated subassembly, the influence of the moderator diminishes, and the influence of Tc-99 acting as an absorber increases, leading to a power decrease in the fuel pins adjacent to the special subassembly. This power increase and decrease could be compensated for by a variable plutonium enrichment around the special subassembly. This is not further investigated.
In Table 3.1, the Tc-99 inventories for cases FR-A to FR-H are given, assuming that the inner core is loaded according to the configuration of the case considered. Also the yearly transmuted Tc-99 masses are given. An interesting phenomenon can be noticed from this table. For cases FR-A to FR-D the yearly transmuted Tc-99 mass increases due to the increase of the Tc-99 inventory. However, the increase from case FR-C to FR-D is very small due to the decreasing number of moderator pins leading to much less moderation. This leads to lower Tc-99 cross sections. The transmuted mass for case FR-F is even lower than for case FR-D due to decreased moderation. For cases FR-G and FR-H the yearly transmuted masses do not change significantly anymore because of the very small increase of the Tc-99 inventory.

Results for a non-moderated subassembly in the inner core
Case FR-H of the previous paragraph contains only Tc-99 pins. The inventory in such case is very high, especially if that is compared with the yearly production of one 1000 MWe LWR, which is only about 20 kg.

It would make sense to reduce the Tc-99 inventory by replacing Tc-99 pins by fuel pins. Four cases with different amounts of Tc-99 loading are investigated. Case FR-I with the tenth layer of the special subassembly loaded with Tc-99 pins, case FR-J with the eighth layer of the special subassembly loaded with Tc-99 pins, case FR-K with the sixth layer of the special subassembly loaded with Tc-99 pins and case FR-L with the fifth layer of the special subassembly loaded with Tc-99 pins. All other positions in the special subassembly are filled with fuel pins in these cases. The geometry for cases FR-I and FR-L are shown in Figures 3.3 and 3.4, respectively.
Results of the calculations are given in Table 3.2. It is seen that the transmutation half lives for these cases are reasonably low, between 15 and 18 years. The yearly transmuted Tc-99 mass reaches about 100 kg, which is the yearly production of about five 1000 MWe LWRs.

Table 3.1: *Results for cases FR-A to FR-H. The enrichment of standard fuel is 19.5 ʷ%.*

Case	Number of Tc-99 pins[a)]	Enrichment (ʷ%)	Power factor[b)]	Neutron flux ($cm^{-2}s^{-1}$)
FR-A	144	35.4	1.30	2.04E15
FR-B	180	34.1	1.12	2.15E15
FR-C	210	33.1	1.01	2.25E15
FR-D	234	32.1	0.95	2.36E15
FR-E[c)]	252			
FR-F	264	30.7	0.88	2.58E15
FR-G	270	29.8	0.87	2.69E15
FR-H	271	29.4	0.87	2.72E15
Case	**Inventory[d)] Tc-99 (kg)**	**Transm rate Tc-99 (kg/a)**	**Tc-99 cross section (barn)**	**Half life (a)**
FR-A	2743	122	0.706	15.3
FR-B	3429	137	0.602	17.0
FR-C	4000	144	0.516	18.9
FR-D	4458	145	0.444	21.0
FR-E[c)]	4800			
FR-F	5029	132	0.326	26.1
FR-G	5143	132	0.306	26.7
FR-H	5162	132	0.301	26.9

a) Number of Tc-99 pins per special subassembly.

b) Power in fuel pins adjacent to special subassembly relative to average power.

c) Not calculated.

d) Inventory when the inner core of 193 assemblies is loaded according to the configuration of the case considered.

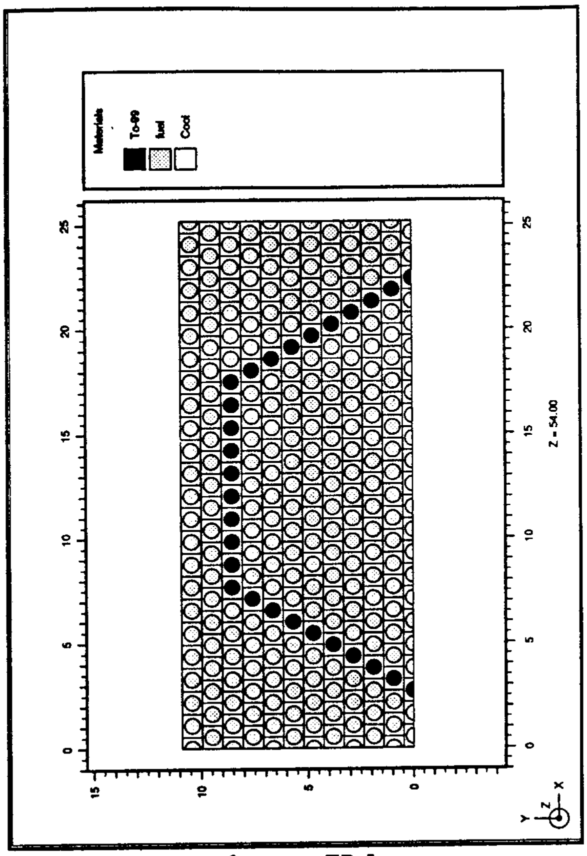

Fig 3.3: *Geometry for case FR-I.*

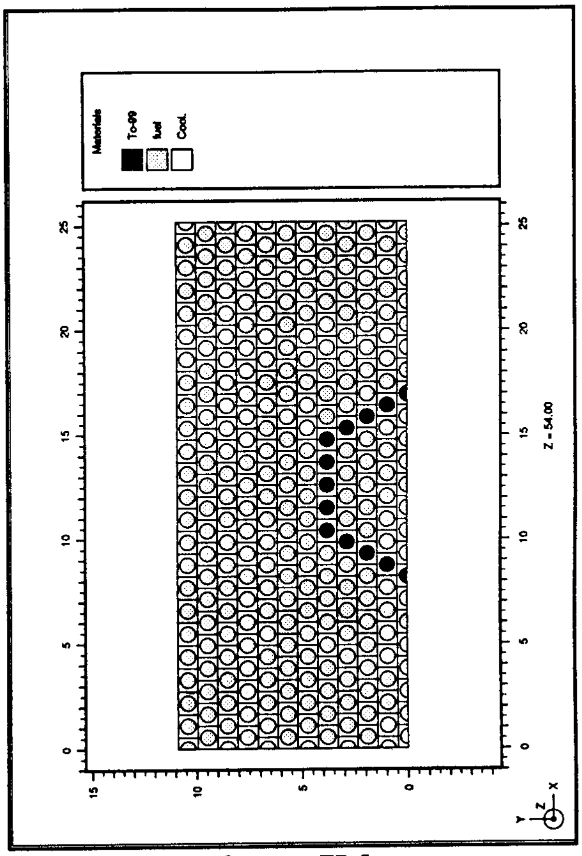

Fig 3.4: *Geometry for case FR-L.*

Table 3.2: *Results for cases FR-I to FR-L. The enrichment of standard fuel is 19.5 ^{w}%. For notes see Table 3.1.*

Case	Number of Tc-99 pins[a]	Enrichment (^{w}%)	Neutron flux ($cm^{-2}s^{-1}$)	
FR-I	54	25.7	3.71E15	
FR-J	42	24.3	3.94E15	
FR-K	30	22.8	4.04E15	
FR-L	24	22.0	4.13E15	
Case	**Inventory[d] Tc-99 (kg)**	**Transm rate Tc-99 (kg/a)**	**Tc-99 cross section (barn)**	**Half life (a)**
FR-I	2662	101	0.331	17.9
FR-J	2071	86	0.340	16.4
FR-K	1479	64	0.345	15.8
FR-L	1183	53	0.350	15.2

Conclusions for the FR

Results on transmutation of Tc-99 in the inner core of a fast reactor are given in this chapter. Both transmutation in a moderated subassembly and in a non-moderated subassembly were considered.

Transmutation in a moderated subassembly has the largest influence on the power distribution in adjacent fuel pins, leading to a necessarily large Tc-99 layer between the moderator pins and adjacent fuel pins, or to a variable plutonium enrichment decreasing towards the periphery of the special subassembly. Most probably this will limit the practical applicability of moderated subassemblies in the inner core of a fast reactor. Nevertheless, when this power peaking is addressed at, the application of a moderated subassembly in the inner core of a fast reactor leads to low transmutation half lives with high yearly transmuted Tc-99 masses.

Transmutation of Tc-99 in a fast reactor seems also possible without moderation. Although the Tc-99 cross section in a non-moderated subassembly is about a factor of two lower than in a moderated one, the neutron flux may be higher, possibly leading to equal transmutation rates. This was actually confirmed by these calculations. Transmutation of Tc-99 in a non-moderated subassembly in the inner core of Superphénix can lead to a gross yearly transmuted Tc-99 mass of about 100 kg with a Tc-99 inventory of 2.7 tonnes. The yearly Tc-99 production in Superphénix equals about 20 kg. This amount is not yet subtracted.

4 Transmutation in Light Water Reactors

Introduction

Light Water Reactors (LWRs) are abundantly present in Western Europe and the US. Transmutation of Tc-99 in LWRs could have the advantage that no special Tc-99 burners are necessary and that each LWR consumes its own produced Tc-99. Then an equilibrium state is achieved and the net production of Tc-99 is zero.

Whether such situation can be achieved or not depends of course on the transmutation rate of Tc-99 in LWRs and on the inventory necessary to transmute the yearly production of one LWR. When this inventory becomes very high it must be concluded that equilibrium with respect to Tc-99 production cannot be achieved practically. The work presented in this chapter is performed in cooperation with Belgo-Nucléaire (see also reference 6).

Model

The modelled PWR corresponds with a Westinghouse type of PWR with a power of 900 MWe.

Calculations on transmutation of Tc-99 were done for both PWRs loaded with UO_2 fuel only (cases LWR-A to LWR-D, see Figure 4.1), and for PWRs loaded with UO_2 fuel for three quarters of the core and with MOX fuel for one quarter of the core (cases LWR-E to LWR-H, see Figure 4.2). In both cases Tc-99 pins with same diameter as fuel pins were modelled in the guide tubes of the core. In the first case the Tc-99 pins were modelled in all guide tubes of the core, in the latter case the Tc-99 pins were modelled in the guide tubes of the MOX fuel only. In both cases the enrichment of the UO_2 fuel was increased to achieve the same average k_∞ as for the corresponding core (full UO_2 or one quarter MOX fuel) without Tc-99 pins. This average k_∞ was obtained by the WIMS package and the accompanied 69-group cross section data library. The enrichment at BOC determined by the WIMS package was then used in KENO Monte Carlo calculations [3] with the 172-group cross section data library based on JEF2.2 to calculate the neutron flux averaged over the Tc-99 target pins in the guide tubes. Resonance shielding of the Tc-99 target pins could then properly be accounted for. Therefore, and also because the WIMS 69-group cross section library is not based on JEF2.2 but on an older evaluated file, the calculations have been performed as described above. The transmutation half lives were calculated according to equation 1.

Results for UO_2 fuel

These cases correspond with a PWR fully filled with UO_2 fuel, where Tc-99 pins with same diameter as fuel pins are inserted in the guide tubes. The different cases correspond with different Tc-99 densities in the target pins of 1, 2, 5 and 10.5 g cm^{-3}. It is assumed that the remaining space in the guide tubes is filled with some inert matrix with zero cross section. The geometry of these cases is given in Figure 4.1. Results are given in Table 4.1. It is seen that the cross section decreases with increasing Tc-99 density. The lowest transmutation half life is obtained for lowest Tc-99 density, and it is seen that in case LWR-A the yearly transmuted Tc-99 mass is still larger than the yearly production of Tc-99, which equals about 18 kg for a 900 MWe PWR.

Table 4.1: *Results for cases LWR-A to LWR-D (full UO_2 core). The enrichment of standard fuel is $3.7^{w}\%$.*

Case	Density Tc-99 (g cm^{-3})	Enrichment U-235 (%)	Neutron flux ($cm^{-2}s^{-1}$)	
LWR-A	1.0	4.5	2.68E14	
LWR-B	2.0	5.1	2.61E14	
LWR-C	5.0	6.5	2.47E14	
LWR-D	10.5	8.6	2.33E14	

Case	Inventory Tc-99 (kg)	Transm rate Tc-99 (kg/a)	Tc-99 cross section (barn)	Half life (a)
LWR-A	726.5	23.7	3.93	20.9
LWR-B	1453	37.2	3.15	26.8
LWR-C	3633	63.8	2.27	39.2
LWR-D	7628	91.7	1.64	57.3

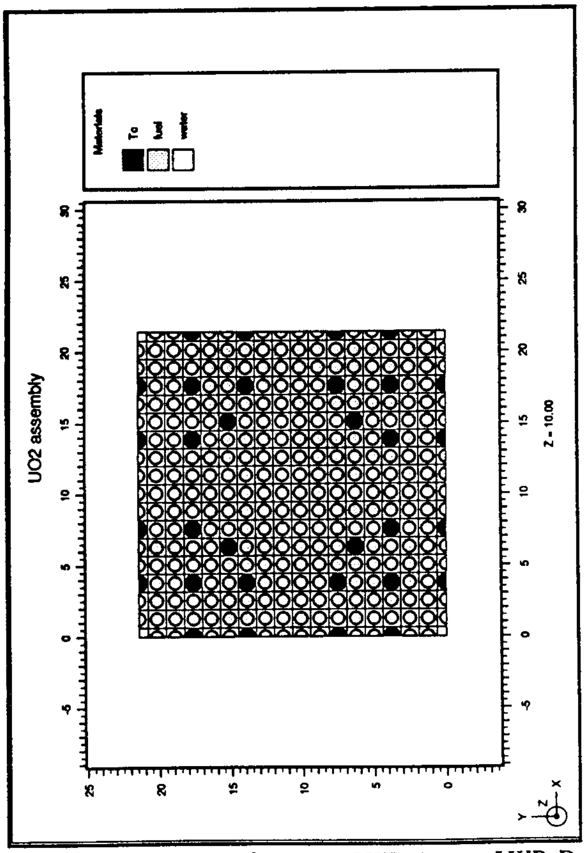

Fig 4.1: *Geometry of cases LWR-A to LWR-D. Four quarters of an assembly with UO_2 fuel are shown.*

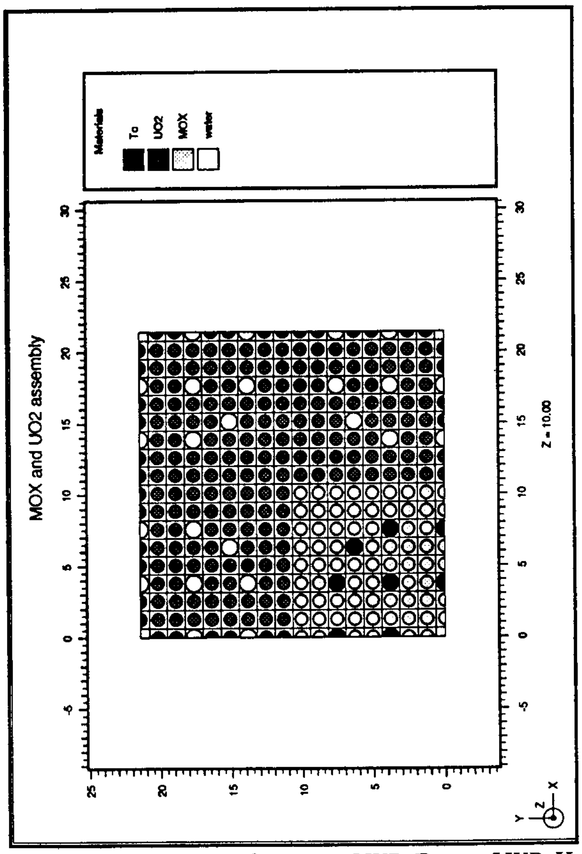

Fig 4.2: *Geometry of cases LWR-E to LWR-H. Three quarters of an assembly with UO_2 fuel and one quarter with MOX fuel are shown.*

Results for MOX fuel
These cases correspond with a PWR filled for three quarters of the core with UO_2 fuel and for one quarter of the core with MOX fuel. Tc-99 pins with same diameter as fuel pins inserted in the guide tubes of the MOX fuel. The different cases correspond again with different Tc-99 densities in the target pins of 1, 2, 5 and 10.5 g cm^{-3}. Again the remaining space in the guide tubes was assumed to be filled with some inert matrix with zero cross section. The geometry of these cases is given in Figure 4.2. Results are given in Table 4.2. It is seen that the transmutation half lives are about 50% larger than for the corresponding cases LWR-A to LWR-D. This is mainly because of the low capture cross sections of Tc-99 in a the harder neutron spectrum characterisitic for MOX fuel. Only for the case with Tc-99 density of 10.5 g cm^{-3}, the transmuted rate is just large enough to compensate for the reactors own yearly Tc-99 production (about 18 kg).

Table 4.2: *Results for cases LWR-E to LWR-H (1/4 MOX, 3/4 UO_2 core). The enrichment of standard fuel is 3.7^w%.*

Case	Density Tc-99 (g cm^{-3})	Enrichment U-235 (%)	Neutron Flux ($cm^{-2}s^{-1}$)	
LWR-E	1.0	4.1	2.31E14	
LWR-F	2.0	4.3	2.26E14	
LWR-G	5.0	4.7	2.15E14	
LWR-H	10.5	5.1	2.03E14	
Case	Inventory Tc-99 (kg)	Transm rate Tc-99 (kg/a)	Tc-99 Cross Section (barn)	Half Life (a)
LWR-E	181.6	4.0	3.10	30.7
LWR-F	363.3	6.3	2.44	39.9
LWR-G	908.2	11.1	1.82	56.4
LWR-H	1907	17.0	1.40	77.4

The dependence of the yearly transmuted Tc-99 mass as function of density is clearly seen in Figure 4.3. Due to resonance and spatial self shielding, the yearly transmuted Tc-99 mass does not show a linear dependence with Tc-99 density. It could be very beneficial to transmute Tc-99 at the lowest possible density.

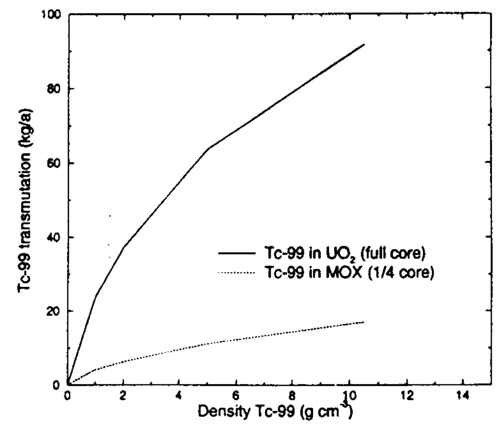

Fig 4.3: *Tc-99 transmutation rate as function of density.*

Conclusions for the LWR
Transmutation of Tc-99 in PWRs lead to rather large transmutation half lives and low yearly transmuted masses. Transmutation in a UO_2 fuelled core has preference above transmutation in MOX fuelled PWRs because of the softer neutron spectrum leading to higher Tc-99 cross sections. Transmutation should be performed at the lowest possible density. Even Tc-99 with density of 1 g cm^{-3} put in all guide tubes lead to yearly transmuted masses of about 24 kg with inventory of about 726 kg. Even for this case it is very

questionable whether breakeven (Tc-99 transmutation equal to Tc-99 production) can be achieved, because in practice not all guide tube are available for transmutation purposes.

5 General Conclusions

To give a ranking of fission reactors with respect to their Tc-99 transmutation capability, the ratio of the yearly transmuted Tc-99 mass and the transmutation half life seems quite reasonable to use as a ranking parameter. This ranking is given in Table 5.1. It must be noticed again that the first case (moderated special subassembly in the inner core of a fast reactor) needs a too high plutonium enrichment (>30^w%). Therefore the inventory and transmutation rate of Tc-99 given in the first row of Table 5.1 should be scaled down to reduce the enrichment need. Also a variable plutonium enrichment decreasing towards the periphery of the special subassembly is needed. Nevertheless this option is expected to yield the best performance for transmutation of Tc-99.

Table 5.1: *Ranking of reactors with respect to Tc-99 transmutation capability.*

React	Configuration	Inventory Tc-99 (kg)	Transm rate Tc-99 (kg/a)	Half Life (a)
FR	Moderated S/A in inner core	3429	137	17
FR	Non-moderated S/A in inner core	2662	101	18
HWR	Pin in moderator	4126	115	25
LWR	Pin in guide tube UO_2 fuel	3633	64	39
LWR	Pin in guide tube MOX fuel	1907	17	77

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