ACTINIDE AND FISSION PRODUCT BURNING IN FAST REACTORS WITH A MODERATOR

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Abstract

Calculations have been carried out with respect to the transmutation of long-lived wastes (minor actinides and fission products) in fast reactors using special devices based on large amounts of moderator material. Such devices can replace both radial and axial blanket sub-assemblies. It has been shown that the implementation of these devices will allow the achievement of long-lived waste burn-up up to a level of 90-95%, decreasing essentially the radiotoxicity of wastes to be buried.

1. Introduction

Spent fuels of modern nuclear reactors contain a rather large quantity of long-lived high-active wastes (plutonium, minor actinides (MA) and fission products (FP)). This amount of waste increases with the electricity production. If plutonium can be used as a fuel for reactors (both thermal and fast), ways should be found for decrease the amount of minor actinides and fission products. Therefore, the major challenge for the future nuclear energy system is the decrease of possible contamination of the environment by such wastes.

Nevertheless, the existing reactors are able to solve these type of problems before development and operation of new promising nuclear systems. However, the implementation of thermal reactors for solving these problems is not efficient due to essential limitations of core physics. The use of traditional fast reactors allows solving the task partially. A homogeneous waste addition to the fuel makes it possible to utilise annually only 15% of all produced MAs in this period and less than 10% of long-lived FP. However, a noticeable degradation of neutronic parameters (increase in sodium void reactivity effect (SVRE) and decrease in Doppler-effect) requires a search for other decisions, more acceptable from a safety perspective.

One of the possibilities involves the implementation of special irradiation devices (ID), which can be located either in radial or in axial blankets. In this case, the effect on core physics will be much less as compared with homogeneous recycling. But the efficiency of transmutation in these devices will be essentially lower.

The efficiency of these devices can be improved by introducing a rather large quantity of moderator. This is related to the fact that practically all FPs have maximum cross-sections in the thermal region and MA cross-sections increase as well when shifting the neutron spectrum to the thermal region. Possibilities for MA and FP efficient transmutation in ID containing moderator are considered in this report for a fast power reactor of BN-800 type as an example.

2. MA burning in special devices located in the radial blanket

Americium oxide located in a magnesium oxide inert matrix is considered as a fuel composition for MA burning. A ratio between volume fraction of americium oxide and magnesium oxide can be varied in such a way that it keeps the total americium loading in the ID.

We noted that fast reactors have an important advantage over thermal reactors for burning minor actinides because their neutron flux is two orders as higher. However, in a fast spectrum, actinides have lower cross-sections compared to a thermal spectrum.

On the basis of these two factors an idea appears to use moderated sub-assemblies (SAs) in fast reactors. In this case we conserve a rather high neutron flux and essentially increase the actinide cross-sections [1].

As an ID, we can consider a core SA in which part of the fuel pins are replaced by pins containing americium oxide in an inert matrix and others are replaced by pins containing a moderator. Varying the number of fuel pins with americium and moderator, one can change a moderator volume fraction in the SA. For a more essential moderator fraction increase, on can use a promising fuel pin design in which the central target material rod (of small diameter, with cladding or without it) is surrounded by a rather thick moderator layer. In this design, it is very easy to vary the ratio of fuel and moderator

volume fractions in a wide range conserving the fuel pin external diameter. This type SA design was used in further studies.

One of the tasks of optimisation studies was a search for moderator material allowing a more efficient actinides transmutation, which all other things being the same. Figure 1 presents the dependency of the capture and fission cross-sections of some actinides on material type and Figure 2 – the dependency of the same cross-sections on moderator volume fraction in the fuel pin for zirconium hydride as the most efficient moderator.

Figure 1. **Dependency of actinide cross-sections on a moderator type**

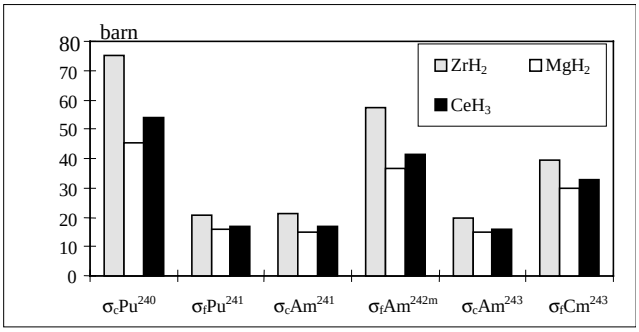
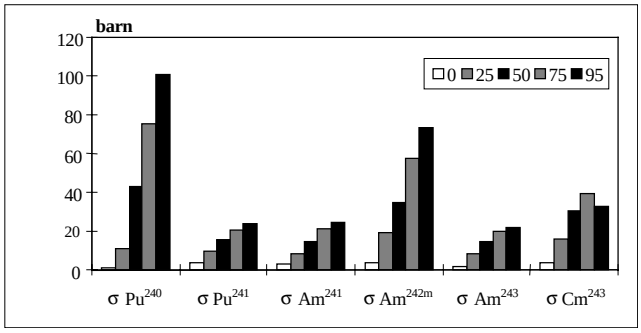
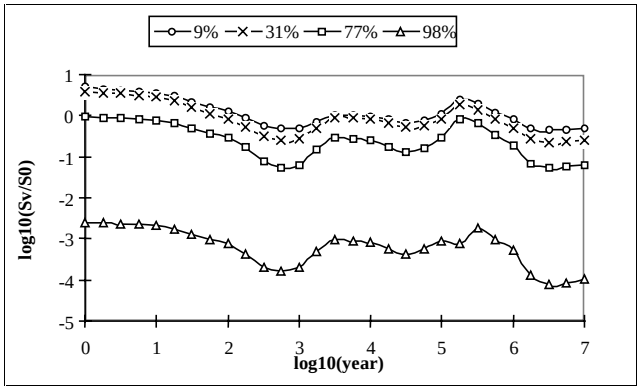


Figure 2. **Dependency of actinide cross-sections on a moderator volume fraction**



We noted that the transmutation of americium in such ID would be worthwhile only if the radiotoxicity of wastes remaining after irradiation is much less than the radiotoxicity of non-irradiated americium. Figure 3 presents the change in waste radiotixicity for different ID burn-ups in reference to storage of non-irradiated americium

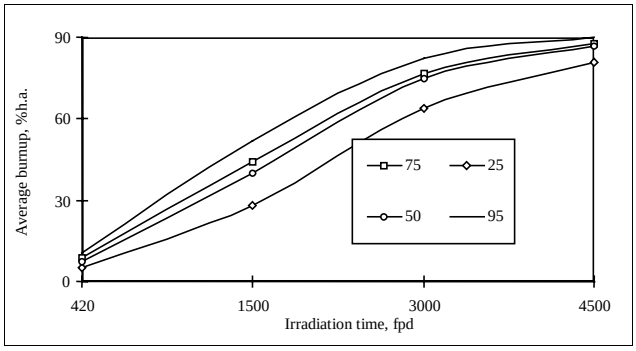
Figure 3. **A change in radiotoxicity of ID wastes for different burn-up relating to storage of non-irradiated americium**



The dependency presented shows that for a decrease in the waste radiotoxocity of at least two orders, it is necessary to reach 93-95% h.a. americium burn-up. Thus, when designing an ID for americium burning, we should start from the necessity to reach just this high burn-up with maximum possible americium loading, and at the same time not to fall outside the existing limitations for basic structure materials of fast reactor cores.

Figure 4 presents the dependency of americium burning value on irradiation time interval for different moderator volume fraction (zirconium hydride).

Figure 4. **Average americium burn-up as a function of irradiation time**



It is easy to see that handling the problem of reaching ~90% h.a. burning requires a long irradiation time (~10-15 years) and a rather high volume moderator fraction in fuel pins (>90%). We noted that long irradiation of SAs with americium will require the development of special reloading regimes. For example, in order to eliminate a high burn-up irregularity over a SA, it is necessary to turn it 180° during irradiation cycle. In this case the maximum damage dose will be ≈200 dpa, which will require a high performance for the structure materials used in these ID. Large changes in ID power with americium burn-up will require the development of a special regime for their cooling. Besides, the introduction of the ID with moderator in the first row of radial blanket will lead to increase in power of adjacent core SAs. The changing in power of these SAs can reach 20-30%. However, in our opinion, this power increase is not critical and will not require special measures.

Thus, in order that americium transmutation in ID is appropriate from the standpoint of essential decrease in actinide radiotoxicity, average americium burn-up should be not less than 90% h.a. This

requires irradiation times beyond 10 years, which, in turn, will require the structure material performing at high damage doses.

The second aspect of long-time irradiation is the dependence of actinide cross-sections and burning efficiency on cycle number. Taking into account that the irradiation time is more than 10 years and core lifetime is approximately one and half a year it is necessary to have ~10 cycles of moderated subassembly irradiations. Dependency of actinide cross-sections on cycle number for two type of sub-assemblies are shown on Figures 5a and 5b.

Figure 5a. **Dependency of cross-sections on cycle number (without moderator)**

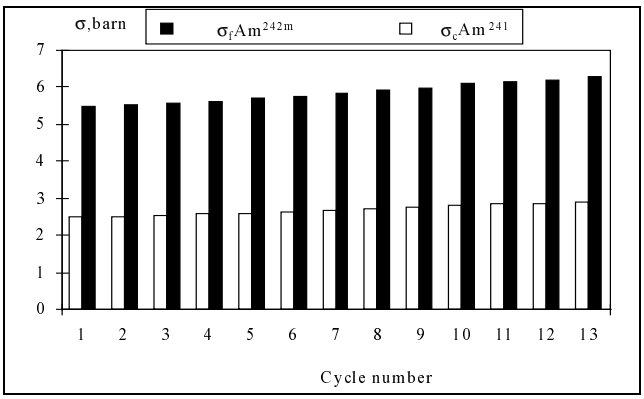
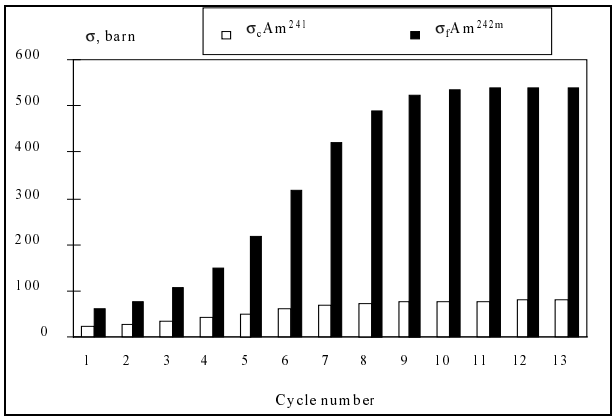


Figure 5b. **Dependency of cross-sections on cycle number (with moderator)**



This dependency shows the cross-sections in moderated sub-assembly reach the maximum value that after approximately 8 cycles. For the non-moderated sub-assembly the cross-sections do not practically depend on cycle number.

3. Influence of moderated sub-assembly on core parameters

To check the influence of moderated sub-assembly with americium on core parameters we investigate the dependency of multiplication factor, target burn-up and sub-assembly power on cycle number.

These dependencies are shown on Figures 6 to 8.

Figure 6. **Dependence of multiplication factor on cycle number**

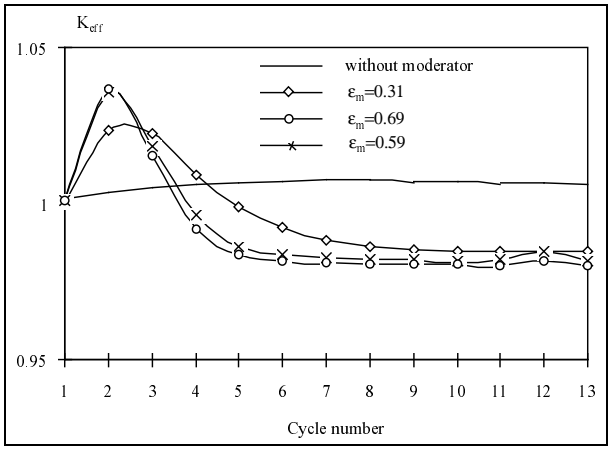


Figure 7. **Dependence of target burn-up on cycle number**

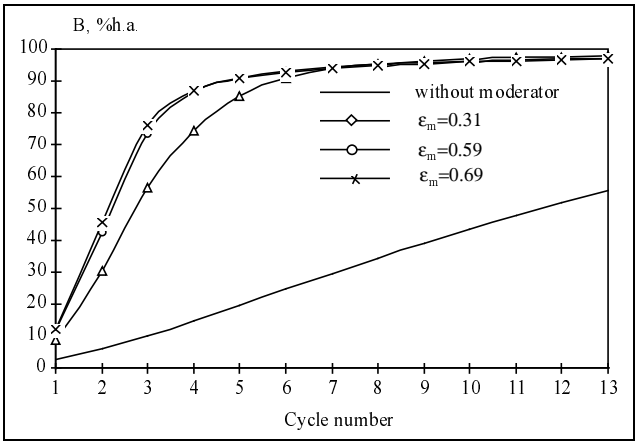
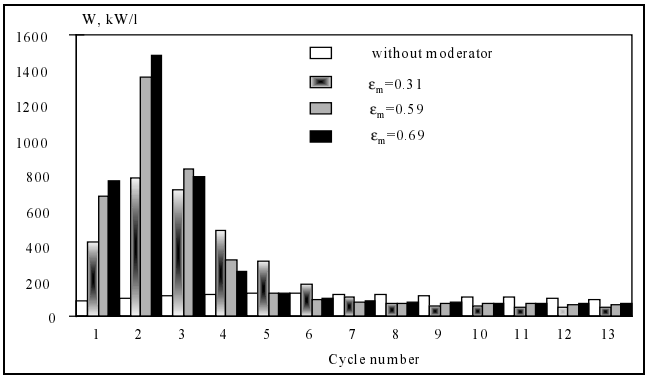


Figure 8. **Dependence of sub-assembly power on cycle number**



The dependencies presented allow making the following conclusions:

- The moderated sub-assemblies have a great influence on critical state of reactor and it is necessary to take special measures to avoid under and sub criticality.
- The power of a moderated sub-assembly is drastically increased during the first cycles of irradiation due to the formation of isotopes with large fission cross-sections (For example, Am242m) and than drops to the nominal level.
- The burn-up of 90% h.a. is reached after 5-6 cycle and the following 5% (up to 95%) requires approximately the same time.

So, the use of moderated sub-assembly for the americium transmutation faces large difficulties, the main of them being the drastically increase of sub-assembly power during irradiation. This can result in decreasing the temperature of target, moderator, steel cladding and possible melting of these components.

4. Fission products transmutation in irradiation devises

Among different FPs, greatly contributing to a long-lived activity, there is the practice of separating a group of several isotopes: ^{99}Tc, ^{107}Pd, ^{93}Zr, ^{135}Cs, ^{129}I, ^{126}Sn and ^{79}Se. The problems of transmuting these isotopes both in thermal and fast reactors have been considered in detail in many publications [2-4]. There is no longer any doubt that a more efficient transmutation of these nuclides is reached in a thermal or close to thermal neutron spectra, since the basic resonance of these FPs are just in this energy range.

Two aspects are considered in this report, connected with FP transmutation in fast reactors with special ID implementation, containing a large moderator quantity:

- The effect of different moderators on the FP transmutation efficiency.
- The effect of irradiation devices on major neutronic core characteristics.

We considered two possible ways to locate the IDs:

- In the first row of the radial blanket.
- Without the lower blanket.

4.1 Technetium-99 transmutation

Transmutation efficiency. ^{99}Tc half-life period is 2.13×10^5 years, and its production in spent fuel of modern power reactors comprises 3.0 kg/TWh for fast reactors and 3.2 kg/TWh for thermal reactors.

Table 1 presents a comparison of ^{99}Tc transmutation when using different moderators.

It should be noted that the introduction of hydrated moderators makes it possible to obtain the most efficient transmutation. The effect of volume moderator fraction on the transmutation rate and absolute value of ^{99}Tc transmutation is presented in Table 2.

When increasing the moderator fraction up to 95%, it is possible to transmute up to 80% of initial loading of the ID during a once-through irradiation, thus providing ~8% per year. Higher transmutation rates (up to 25%/year) can be provided by an ID located in the axial blanket.

Table 1. **Comparison of ^{99}Tc transmutation efficiency when using different moderators**

Moderator	**Radial blanket**		**Axial blanket**	
	%/cycle	kg/TWh	%/cycle	kg/TWh
CaH_2	77.3	2.29	35.7	5.33
MgH_2	77.3	2.29	35.7	5.33
TiH_2	71.5	2.12	31.2	4.66
CeH_3	74.6	2.21	33.5	5.01
ZrH_2	72.1	2.14	31.7	4.73
Be	64.0	1.90	26.2	3.92
C	60.1	1.78	24.0	3.58
Be_2C	65.3	1.94	27.1	4.04
$NbBe_{17}$	63.5	1.88	25.9	3.87

Table 2. **Effect of moderator volume fraction on ^{99}Tc transmutation efficiency (radial blanket/axial blanket)**

	Moderator volume fraction (CaH_2), %			
	0	22	80	95
%/cycle	11.2/3.4	15.4/4.8	44.0/15.6	77.3/35.7
kg/TW*h	6.0/9.6	7.3/11.1	5.9/10.2	2.3/5.3

However, a small irradiation time (~1.5 year) allows to burn in one cycle only 35% of the loaded technetium.

Thus, the introduction of a moderator in ID allows an important increase in the transmutation rate. However, a decrease in this case of the total FP results in a decrease of absolute value of transmuted technetium.

It should be noted that even an essential decrease of the quantity of long-lived FPs as a result of the irradiation does still not solve the problem of the activity decrease. It is due to the build-up of other nuclides from which the radioactivity could exceed the one of the target nuclide. In the case implying ^{99}Tc, this problem does not exist, since during the irradiation a short-lived ^{100}Tc isotope and two stable ruthenium isotopes are produced. The calculation results are presented in Table 3.

Table 3. **Different isotope contribution into activity after irradiation of ^{99}Tc, Cu/kg**

Isotope	Loading	Discharge	After cooling, year		
			3	100	1000
Tc^{99}	17.05	3.5	3.5	3.5	3.5
Tc^{100}	–	5.26 + 5	–	–	–
Total	17.05	5.26 + 5	3.5	3.5	3.5

Thus, the ID activity will be defined by ^{99}Tc both before and after irradiation.

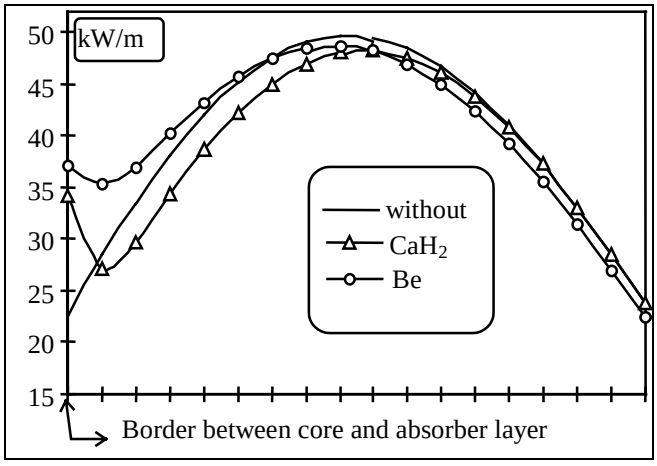
The presented results indicate a rather high efficiency of technetium transmutation in ID with a moderator. However the required transmutation efficiency should be determined from an economical point of view. Small technetium quantity transmuted in an irradiation cycle, even for a rather high transmutation rate, will require much more cycles of irradiated target processing, which increase irretrievable losses. Larger transmutation volumes, with low transmutation rate, require either a larger number of IDs in the reactor or an increase in reactor number, which should be loaded by IDs.

4.2 The effect moderator in the blanket on core neutronic parameters

We will consider the effect of a moderator in the axial blanket on the core parameters for ^{99}Tc transmutation.

First of all, we noted that the moderator location in the immediate vicinity of the core leads to the production of thermal neutrons in the moderator which re-enter the core, increasing sharply the fission rate and, therefore, the power in the nearest core layers. It is obvious in the Figure 9, which shows an axial power field in most fuel pins of the core.

Figure 9. **Axial power distribution for various moderators in axial blanket**

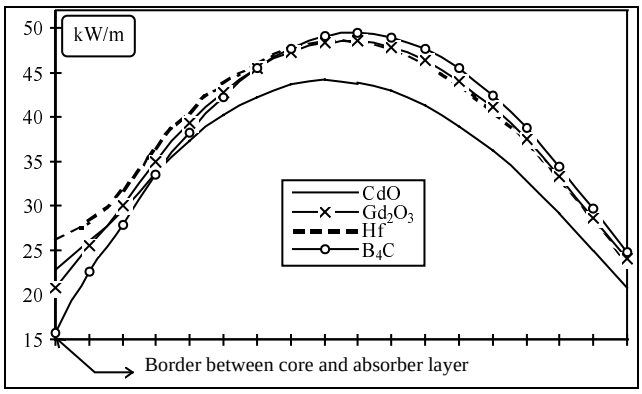


It is necessary in this case to pay attention to the fact that the use of hydrated moderators leads to a very sharp power increase in the region adjacent to the blanket. The power at the boundary between the core and the blanket increases to 80%.

Even greater power increases are observed when using a beryllium moderator, although in this case the power increase takes place smoothly along the height of the lower core half. The question if one of these cases is more dangerous from the standpoint of reactor safety requires the performance of detailed thermal-hydraulic calculations.

However, the effect of moderator on the power distribution can be essentially decreased by the introduction of an absorber layer between the core and the blanket with moderator. The Figures 9 and 10 present the axial power distributions when introducing a layer of different type absorber.

Figure 10. **Axial power distribution for various absorber in layer between core and axial blanket (moderator CaH_2)**



These distributions show that best results are achieved when using an absorbing layer with cadmium oxide. In this case, not only the power at the boundary decreases but also the maximum power value decreases. We noted that when beryllium is used as a moderator, the effect of absorbers on the power fields is only observed in the immediate vicinity of the blanket.

The effect of the absorber introduction on transmutation efficiency and SVRE value are considered further on. The calculation results are presented in Table 4.

Table 4. **The effect of absorber on transmutation efficiency and SVRE value**

	Moderator CaH_2				
Absorber	–	CdO	Gd_2O_3	Hf	B_4C
kg/TWh	5.29	4.59	3.36	3.79	1.90
SVRE, %Δk/k	-0.169	+0.145	-0.100	-0.102	-0.311
	Moderator Be				
Absorber	–	CdO	Gd_2O_3	Hf	B_4C
kg/TWh	3.76	3.56	2.13	2.38	1.79
SVRE, %Δk/k	+0.339	+0.650	+0.171	+0.188	+0.109

The results presented show that the introduction of CaH_2 as a moderator decreases SVRE value to ~0.5%Δk/k comparing to the use of beryllium. The implementation of different absorbers changes the SVRE value in the limits of 0.5 %Δk/k.

Thus, the introduction of an absorber solves the power distribution problem and at the same time leads to a decrease in the FP transmutation efficiency. But if CdO is used as an absorber, the decrease of the transmutation efficiency does not exceed 15%.

4.3 Iodine-129 transmutation

^{129}I has the largest among all long-lived wastes half-life period, equal to 1.57×10^7 years, and its production amounts are about 0.7 kg/TWh for fast reactors and 0.66 kg/TWh for thermal reactors.

To consider ^{129}I transmutation, it is necessary to choose the best chemical form for a material containing large quantities of ^{129}I. Among different chemical compositions, three compositions are considered as target materials: BeI_2, NaI, CeI_3, the latter having the largest number of ^{129}I nuclei [5]. Table 5 presents a comparison of ^{129}I transmutation efficiency for different moderators and three chemical composition stabilising iodine

Table 5. **A comparison of ^{129}I transmutation for different chemical compositions**

	BeI_2		**NaI**		**CeI_3**	
	kg/TWh	%/cycle	kg/TWh	%/cycle	kg/TWh	%/cycle
MgH_2	0.71	29.3	1.17	28.6	1.25	28.8
ZrH_2	0.71	29.2	1.17	28.6	1.25	28.8

It is necessary to pay attention to the fact that the introduction of BeI_2 allows the assurance of a maximum transmutation rate, whereas introducing CeI_3 provides the largest absolute transmutation efficiency. The results regarding the BeI_2 composition are presented.

The comparison of ^{129}I transmutation efficiency for implementation of different moderators is given in Table 6.

Table 6. **I^{129} transmutation efficiency when using different type moderators**

Moderator	**Radial blanket**		**Axial blanket**	
	%/cycle	kg/TWh	%/cycle	kg/TWh
CaH_2	65.2	0.32	27.0	0.66
MgH_2	68.7	0.33	29.3	0.71
TiH_2	52.2	0.25	19.8	0.48
CeH_3	67.8	0.33	28.7	0.70
ZrH_2	68.6	0.33	29.2	0.71
Be	50.3	0.24	18.7	0.46
C	41.6	0.20	14.8	0.36
Be_2C	51.3	0.25	19.3	0.47
$NbBe_{17}$	47.7	0.23	17.6	0.43

Because the ^{129}I capture cross-section has a clearly defined maximum in the thermal range, the best results are obtained when using hydrated moderators (MgH_2, CeH_3, ZrH_2).

The effect of a moderator volume fraction on the transmutation rate and absolute quantity of iodine transmuted is presented in Table 7.

Table 7. **The effect of moderator volume fraction on ^{129}I transmutation efficiency (radial blanket/axial blanket)**

	Moderator volume fraction (ZrH_2) %			
	0	25	70	95
%/cycle	18.2/5.7	35.2/12.0	62.1/25.1	68.6/29.2
kg/TWh	1.8/2.3	2.7/4.6	1.3/2.6	0.33/0.71

An analysis of activity changing for ^{129}I and the products of its irradiation is presented in Table 8.

Table 8. **Different isotope contribution to activity after ^{129}I irradiation, Cu/kg**

Isotope	**Loading**	**Discharge**	**After cooling, year**		
			3	100	1000
^{129}I	0.18	0.05	0.05	0.05	0.05
^{130m}I	–	62 272.73	–	–	–
^{130}I	–	1.15+5	–	–	–
^{131}I	–	68.18	–	–	–
^{131m}Xe	–	595.45	–	–	–
^{133m}Xe	–	1.68	–	–	–
^{133}Xe	–	23,55	–	–	–
^{134m}Cs	–	0.8	0.64	–	–
^{134}Cs	–	1.75	–	–	–
Total	0.18	1.77+5	0.69	0.05	0.05

Contrary to ^{99}Tc, an irradiation of ^{129}I leads to the creation of e.g. ^{134m}Cs while the activity of these will define the activity of irradiated targets activities during some time (~30 years). Nevertheless, the irradiation of iodine is also a rather efficient method to decrease the FP radioactivity. However, it is necessary to pay attention to the fact that the irradiation products are also gaseous xenon isotopes (^{130}Xe, ^{131}Xe and ^{132}Xe) creating a rather high pressure in the used targets.

4.4 Palladium-107 transmutation

^{107}Pd has a half-life period of 6.5×10^6 years, and its production in the power reactor fuel amounts: 1.54 kg/TWh for fast reactors and 0.78 kg/TWh for thermal reactors.

The effect of different moderators on ^{107}Pd transmutation efficiency is presented in Table 9.

Table 9. **^{107}Pd transmutation efficiency when using different moderators**

Moderator	**Radial blanket**		**Axial blanket**	
	%/cycle	kg/TWh	%/cycle	kg/TWh
CaH_2	63.4	1.89	25.9	3.90
MgH_2	64.0	1.91	26.2	3.95
TiH_2	52.9	1.58	20.1	3.02
CeH_3	58.1	1.73	22.8	3.43
ZrH_2	57.1	1.71	22.3	3.36
Be	77.0	2.30	35.4	5.33
C	67.8	2.03	28.7	4.31
Be_2C	77.9	2.32	36.2	5.45
$NbBe_{17}$	74.6	2.23	33.5	5.05

Contrary to the technetium and iodine, the highest efficiency of palladium transmutation is provided by using beryllium containing moderators.

The effect of moderator volume fraction on the transmutation rate and absolute quantity of transmuted palladium is presented in Table 10.

Table 10. **The effect of moderator volume fraction on ^{107}Pd transmutation efficiency**

	Moderator volume fraction(Be_2C) %			
	0	25	70	95
%/cycle	9.6/2.9	22.7/7.2	49.7/18.2	77.9/36.2
kg/TWh	5.8/8.7	10.6/16.9	6.5/12.0	2.32/5.45

The analysis results for palladium irradiation product activity are presented in Table 11.

Table 11. **Different isotopes contribution to activity after ^{107}Pd irradiation, Cu/kg**

Isotope	Loading	Discharge	After cooling, year		
			3	100	1 000
^{107}Pd	0.51	0.11	0.11	0.11	0.11
^{108}Ag	–	0.33	–	–	–
^{108m}Pd	–	5641.60	–	–	–
^{108}Pd	–	77589.41	–	–	–
^{109m}Ag	–	3.53+5	–	–	–
^{110m}Ag	–	1.31+5	632.00	–	–
^{110}Ag	–	3.30+5	8.85	–	–
^{111m}Pd	–	5.0	–	–	–
^{111}Pd	–	31.76	–	–	–
^{111}Ag	–	32.4	–	–	–
^{111m}Cd	–	102.8	–	–	–
^{113m}Cd	–	0.73	0.63	–	–
^{115}Cd	–	2.87	–	0.01	–
Total	0.51	1.06+6	642.1	0.12	0.11

The results presented show that the irradiated palladium activity increases several orders due to the creation of short-lived nuclides (^{110m}Ag, ^{110}Ag), which then falls quickly, and after approximately 30 years the targets activity will be again defined by palladium only.

4.5 Caesium-135 transmutation

^{135}Cs has a half-life time of 2.3×10^6 years, and its production in the power reactor fuel amounts: 3.7 kg/TWh for fast reactors and 1.4 kg/TWh for thermal reactors.

When analysing the calculation results for possibility to transmute ^{135}Cs in the targets with a moderator, as presented in Table 12, a conclusion can be made that in case of ^{135}Cs irradiation the choice of moderator does not play an important role, since all moderators give approximately the same results.

It should be noted that the caesium transmutation rate is somewhat lower compared to the nuclides considered above, which is explained by a lower capture cross-section.

Table 12. **^{135}Cs transmutation efficiency when using different moderators**

Moderator	Radial blanket		Axial blanket	
	%/cycle	kg/TWh	%/cycle	kg/TWh
CaH_2	44.7	0.40	16.2	0.72
MgH_2	44.8	0.40	16.2	0.72
TiH_2	33.6	0.30	11.5	0.51
CeH_3	39.0	0.35	13.7	0.61
ZrH_2	40.2	0.36	14.2	0.64
Be	40.3	0.36	14.2	0.64
C	41.3	0.37	14.7	0.65
Be_2C	47.3	0.42	17.4	0.78
$NbBe_{17}$	42.7	0.39	15.3	0.68

Besides, other caesium isotopes (^{133}Cs, ^{137}Cs etc.) are accumulated in power reactor spent fuel and the Cs^{135} fraction is ~10% only. When transmuting caesium without chemical isotope separation, the transmutation efficiency decreases one order due to creation secondary ^{135}Cs.

Thus, the results presented show that the issue on advising to transmutate ^{135}Cs in reactor conditions remains open.

The transmutation of ^{93}Zr ($T_{1/2} = 1.53 \times 10^6$ years, production 1.74 kg/TWh for fast reactors 2.8 kg/TWh for thermal reactors) was not considered in detail in this report due to large uncertainties in its nuclear data.

The transmutation of such elements ^{79}Se ($T_{1/2}$ = 65 000 years) and ^{126}Sn ($T_{1/2} = 10^5$ years) is not considered because of their low transmutation rate.

The analysis results allow forming the final Table 13.

Table 13. **A comparison of transmutation rate for different FP and their production in power reactors.**

Isotope	$T_{1/2}$	Production in reactors, kg/TWh	Transmutation efficiency kg/TWh	
			without moderator	with moderator
^{99}Tc	2.13×10^5	3.0/3.2	10.6	5.3
^{107}Pd	6.5×10^6	1.54/0.78	5.5	3.0
^{135}Cs	2.3×10^6	3.70/1.4	5.1	0.8
^{129}I	1.57×10^7	0.70/0.66	5.3	0.7
^{79}Se	6.5×10^4	0.03/0.02	0.09	0.01
^{126}Sn	10^5	0.15/0.08	0.2	0.04
^{93}Zr	1.53×10^6	1.74/2.8	2.3	1.4

Thus the transmutation of such FPs ^{99}Tc, ^{107}Pd and ^{129}I with the use of moderators in IDs is rather proved, since their transmutation efficiency exceeds their production. The transmutation of ^{135}Cs, ^{93}Zr in such blanket can turn out to be not useful, and a further optimisation of the moderator quantity is necessary. Moreover, ^{135}Cs will require its separation from other Cs isotopes produced in spent fuel.

5. Conclusion

The considered method for radioactive wastes (actinides and fission products) transmutation in special irradiation devices containing large moderator quantity has essential advantages over the homogeneous method for these wastes to be recycled.

The results presented have shown that to decrease the americium radiotoxicity significantly, a very high actinide burn-up (up to 95% h.a.) should be achieved in these irradiation devices. In this case up to 60 kg of americium per year will be destroyed. Such quantity is accumulated presently in all VVER-100 reactors in Russia.

But this method faces large difficulties in realising such core with moderated sub-assemblies. It is necessary to take special measures to avoid the large power increase in moderated sub-assembly during irradiation.

The major long-lived fission products can be also transmuted in such irradiation devices. However, isotope separation will be needed to increase the transmutation efficiency of ^{135}Cs and ^{93}Zr isotopes, for example. The major advantage of the use of this fission product utilisation concept consists in the decrease of total losses in each step of waste reprocessing. Nevertheless, a serious contradiction should be pointed out between the transmutation rate and absolute quantity of utilised fission products.

The influence of irradiation devices with a moderator on some core neutronic parameters has been considered. And it has been shown that the implementation of absorbing blankets, made from cadmium oxide, will allow an essential decrease in the effect of such devices on the core parameters, decreasing slightly the transmutation efficiency.

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