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Document Title

Feasability of Burning Plutonium and Minor Actinides in Prismatic Blocks HTRs

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1. INTRODUCTION

For a few years, the High Temperature Gas cooled Reactor (HTGR) technology has gained worldwide new interest due to its specific characteristics. It is a promising reactor concept for the next generation of nuclear power applications. In addition to the studies performed on the industrial concept (uranium core type), there is a strong interest in the development of a «Deep Burner» version of HTGRs, dedicated to minor actinides destruction.

At the CEA, the actinides burner version of the prismatic block-type reactor is currently investigated, including studies about the design proposed by General Atomics [1, 2]. Advanced HTGRs allow a simplification of safety through reliance on innovative features and passive systems. One of the innovative features in HTGRs is the ceramic-coated fuel particle, which can retain the fission products even under severe accident conditions. The other original feature is the annular configuration of the core, surrounded by internal and external graphite reflectors able to evacuate decay heat in accidental conditions. The growing interest in HTGRs activities has shown the need to validate the tools and techniques developed for reactor physics calculations. The physics of the deep-burn transmutation concept is still complicated due to the fact that two fuel types, DRIVER and TRANSMUTER, are loaded in the core. Same ceramic-coated particle technology is used to fabricate both fuel types but particles are sized differently so as to favour immediate fissions in the driver fuel, or absorption followed by fissions in the transmutation fuel. Furthermore, self-shielding effects are of great importance to calculate HTGR fuel cycle or temperature coefficient correctly.

The purpose of this document is essentially to evaluate some physical aspects of the Deep-Burn concept. The major part of the results presented in this document are issued from fuel element calculations in infinite medium. These calculations aim at evaluating, in a simplified configuration, the impact of some design options such as plutonium and minor actinides located in different coated fuel particles and fuel compact. By using simplified calculations, we have tried to find the optimum configuration for which the plutonium and minor actinides consumption is enhanced. In the second part, the analysis deals with the core geometry in order to estimate the impact of some physical assumptions on the fine fuel isotopic depletion.

2. REFERENCE REACTOR MODEL

2.1. Introduction concerning the fuel management

The preliminary analysis presented in this document aims at evaluating the impact of some specific design options on the plutonium and minor actinides consumptions. One of these options concerns the heterogeneous loading of plutonium and minor actinides in the fuel element.

In the "Deep-Burn concept" [2], the plutonium and the minor actinides are loaded in two different fuel compacts. On the one hand, the plutonium coming from Light Water Reactor (LWR) irradiated fuel assembly is loaded in a fuel compact called DRIVER compact. On the opposite, the minor actinides coming from LWR but also all the heavy nuclides that have not been burnt in the DRIVER fuel in a previous core irradiation are loaded in a fuel compact called TRANSMUTER compact.

One of the main advantage of this design (and of the HTR design in general) is the capability to adapt the core design to the type of fuel loaded into the core. This can be done by adjusting the number of fuel compacts and their spatial distribution in the fuel element, changing the size of the coated fuel particles, changing the number of coated fuel particles loaded per fuel compact… It allows to modify the local neutron spectrum and then to improve the consumption of the heavy nuclides.

2.2. Main core design features

The main features of the core loaded with plutonium and minor actinides are indicated in Figure 1 and Figure 2 [2]. The core design is very close to GT-MHR's one. In this configuration, the core is loaded with 780 standard fuel elements and 300 control fuel elements.

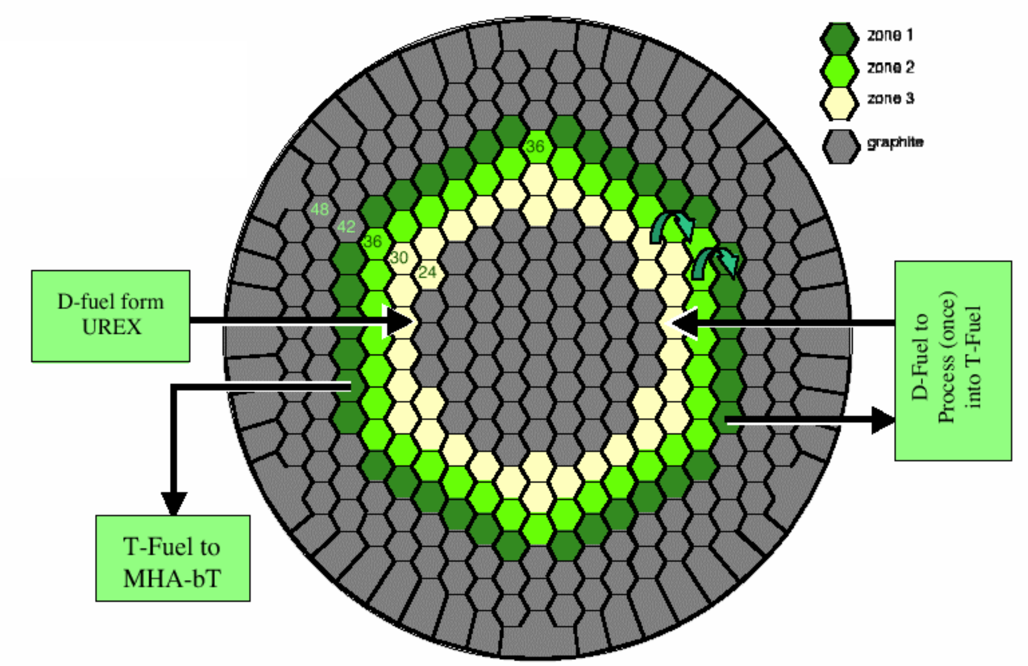


Figure 1: Deep-Burn concept - core geometry

The standard fuel element is 36.0 cm across opposite sides and has a total height of 80.0 cm. The graphite matrix of the element can receive 216 rods corresponding to the position of the fuel rods. A fuel rod consists of a vertical stack of 15 compacts with a unit height of 4.928 cm. The "active" length of a fuel rod (i.e. that occupied by fuel or burnable poison) is 73.92 cm. The remaining space (i.e. a length of some 6.0 cm divided between the top and the bottom of the element) is occupied by graphite caps. There is therefore no fissile matter in the upper and lower parts.

For the analysis, two types of fuel rods have been taken into account. On the one hand, the DRIVER rods are loaded with plutonium based fuel. There are 144 DRIVER rods in the standard fuel element and 126 DRIVER rods in the control fuel element.

On the other hand, the TRANSMUTER rods are loaded with both minor actinides and all the heavy nuclides extracted from the irradiated DRIVER fuel. There are 72 TRANSMUTER rods in the standard fuel element and 62 TRANSMUTER fuel rods in the control fuel element.

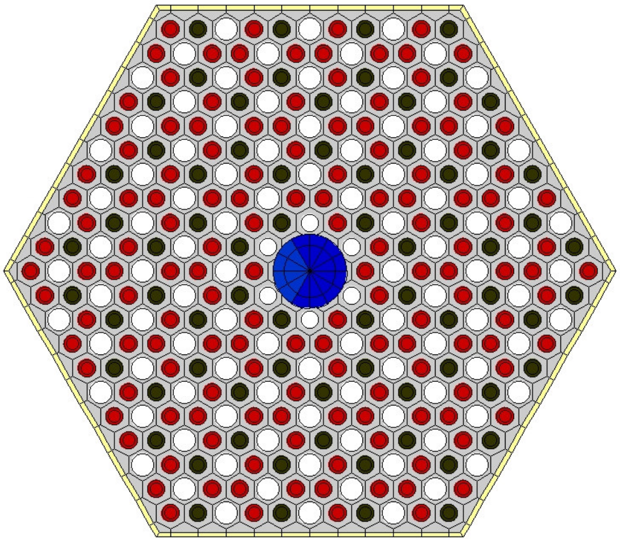


Figure 2: Deep-Burn concept - Standard fuel element geometry
Driver compact in Red – Transmuter compact in Green

2.3. Categories of fuel investigated

In this document, we will focus on the equilibrium cycle evaluated from previous studies [3]. The compositions of both DRIVER and TRANSMUTER fuel at equilibrium cycle are presented in Figure 3. The DRIVER fuel contains roughly 68,8 % of fissile plutonium whereas the TRANSMUTER fuel contains about 63,5 % of plutonium (degraded plutonium with only 28,8 in fissile plutonium). The total mass of DRIVER fuel loaded into the core is 900 kg while the total mass of TRANSMUTER fuel is 400 kg.

Driver Fuel (initial)	
Total	900
Np-237	5.2 %
Pu-238	1.5
Pu-239	57.0
Pu-240	23.0
Pu-241	8.3
Pu-242	5.0
Am-241	
Am-242	
Am-243	
Cm-244	
Cm-245	

Transm. Fuel (initial)	
Total	400
Np-237	5.8 %
Pu-238	4.5
Pu-239	2.4
Pu-240	20.9
Pu-241	15.8
Pu-242	19.9
Am-241	21.0
Am-242	0.2
Am-243	7.7
Cm-244	1.7
Cm-245	0.1

Figure 3: Isotopic composition of the DRIVER and TRANSMUTER fuel used for the analysis

3. CODE AND CALCULATION METHODS

The neutronics analysis presented here is essentially based on a specific calculation process employing the APOLLO2 [4] transport code which is a part of the code system SAPHYR.

The formalism used to solve the multigroup Boltzmann transport equation is either the Integral-Equation (P_{ij}: collision probability 1D and 2D) or Integral-Differential-Equation (S_n: discrete ordinates and nodal methods in 2D). The standard 172-group cross section library issued mainly from JEF 2.2 is used in the present study. The standard depletion chain consists of 24 heavy nuclei (till Cm^{248}) and 77 fission products.

Seven of the principal heavy nuclides (Pu^{238} to Pu^{242}, Am^{241} and Am^{243}) are self shielded during the fuel depletion. An example of the standard fuel element described with a hexahedral multicell geometry is given in Figure 4. The calculations have been performed in fundamental mode (critical buckling), considering a linear anisotropic collision hypothesis for the calculation of the graphite diffusion coefficient.

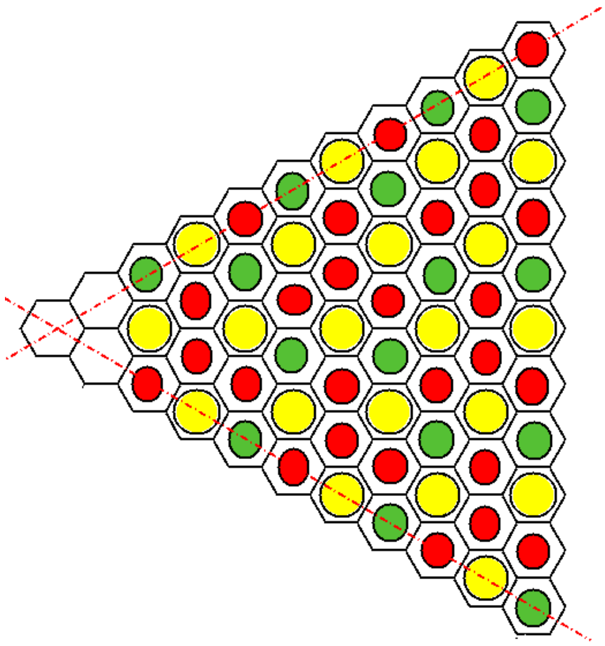


Figure 4: Deep-Burn concept - Fuel element modelling in APOLLO2

4. PRELIMINARY ANALYSIS ON “FRESH” FUEL ELEMENT

4.1. Objective of the analysis

The aim of loading plutonium and minor actinides in two different types of fuel compacts is to improve their consumption by adjusting locally the neutron spectrum to the specificities of the fuel. For example, the improvement of the plutonium consumption in the DRIVER compact is strongly dependant to the increase of thermal neutrons in this compact. Indeed, the thermal neutrons induce more fissions and allows to produce many neutrons useful for the minor actinides transmutation. This could be achieved by decreasing the mass of plutonium loaded or increasing the size of the coated fuel particles. On the opposite, the improvement of the minor actinides consumption in the TRANSMUTER compact is strongly dependant to the spectrum hardening (the spectrum hardening in the TRANSMUTER compact increases the capture rates in the resonance).

This section aims at evaluating the impact of some parameters such as the size of the DRIVER coated fuel particles and the mass of DRIVER fuel on the capture and fission rates in the DRIVER compact. The analysis is performed on the "fresh" fuel element loaded with first generation plutonium.

4.2. Results and comments

Some of the results obtained on the fuel element geometry are gathered in Figure 5, Figure 6 and Figure 7. The mass of DRIVER fuel loaded into the core has a strong impact on the fuel element $k_{infinity}$. By increasing the mass of DRIVER, it reduces the "net" number of neutrons available for the transmutation of the minor actinides. Furthermore, the increase of the DRIVER fuel mass induces a steady increase of the capture rates in the DRIVER fuel (see Figure 6). In the same time, the thermal fission rate in the DRIVER fuel particles reaches an optimum with respect to the mass of DRIVER fuel loaded into the core. It must be noticed that the coated fuel particle dimension may play an important role. Indeed, the increase of the DRIVER particle diameter allows to improve both the spatial self shielding and the thermal fission. However, in any cases, whatever the mass of fuel or the size of the particle are, the ratio between the Pu^{239} fission rate and the total coated fuel particle absorption rate does not exceed 65 % (see Figure 7).

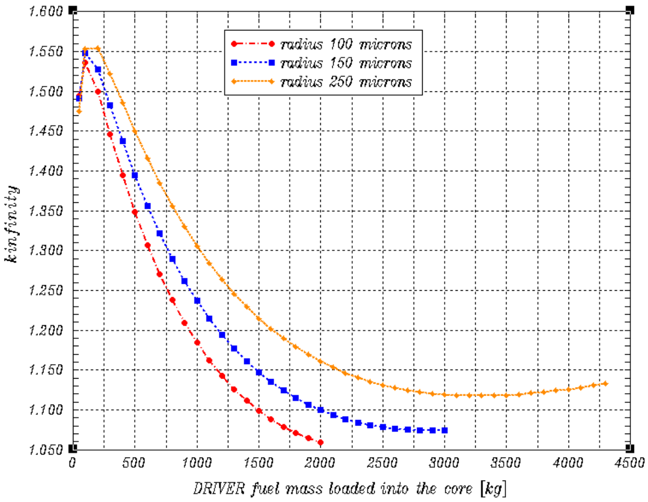


Figure 5: Impact of the DRIVER fuel mass loaded into the core on the fuel element $k_{infinity}$

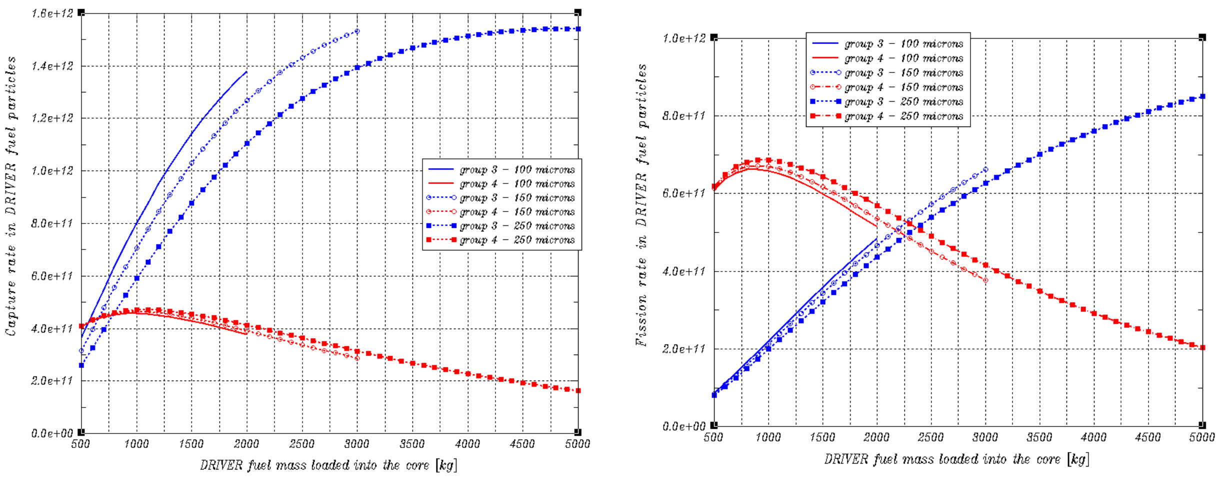


Figure 6: Impact of the DRIVER fuel mass loaded into the core on the DRIVER fuel capture and fission rates

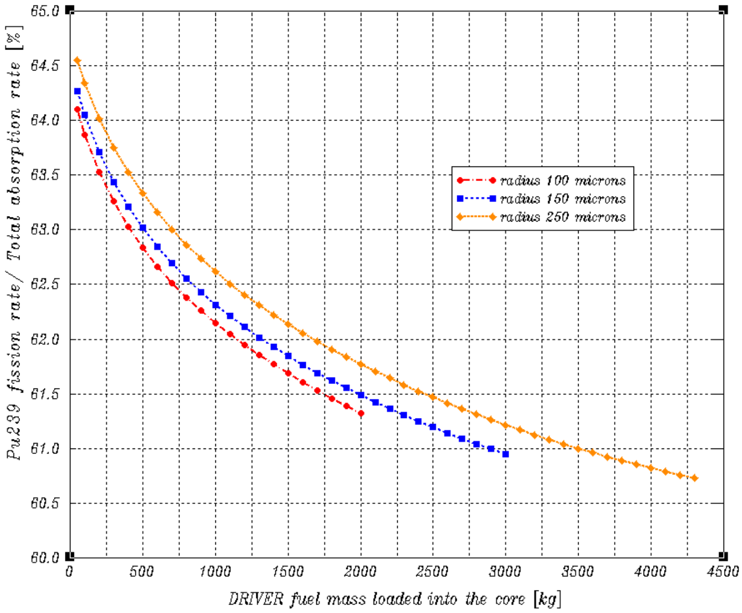


Figure 7: Impact of the DRIVER fuel mass loaded into the core on the ration Pu^{239} fission rate/Total absorption rate

4.3. Preliminary conclusion

From this analysis, it can be said that, for the fuel element loaded with fresh DRIVER fuel, the moderating ratio has a strong impact on the plutonium utilisation and moreover on the Pu^{239} fission rate. The optimum mass of DRIVER fuel loaded into the core is roughly 900 kg while the plutonium utilisation is favoured by using large size of coated fuel particles (~ radius of 300 µm).

5. FUEL ELEMENT DEPLETION ANALYSIS

5.1. Introduction

In this section, we have performed the fuel element depletion calculation in fundamental mode (critical buckling search). In the reference state, 900 kg of DRIVER fuel and 400 kg of TRANSMUTER fuel are loaded into the core. The analysis is performed by comparing the impact of parameters such as the coated fuel particles size (both DRIVER and TRANSMUTER particles) and the mass of TRANSMUTER fuel on the fuel element concentrations during fuel depletion.

5.2. Fuel element neutron spectrum during fuel depletion

An illustration of the average fuel element neutron spectrum during fuel depletion is given in Figure 8. In the core configuration, the number of thermal neutrons is much more larger than in fundamental mode. This is due to the reflector impact on core neutron spectrum. However, whatever the fuel element burnup is, the energy corresponding to the thermal neutron spectrum peak is roughly 0,15 eV. This energy is higher than the energy range where the ratio between capture to fission is the smallest (energy << 0,1 eV, see Figure 9).

As to conclude, it can be said that HTR design offers the capability to modify many parameters so as to soft the neutron spectrum. However, the physical impact of such modifications are limited and quite far from "theoric best configuration" (highly thermal flux for the DRIVER and epithermal flux for the TRANSMUTER)

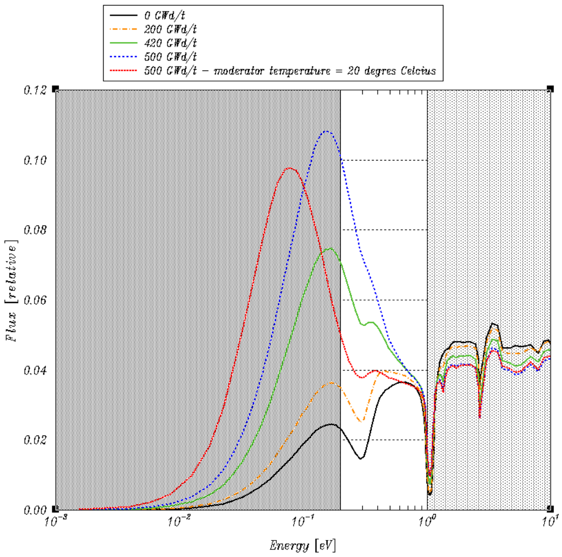


Figure 8: Variation of the average neutron spectrum in the fuel element during fuel depletion

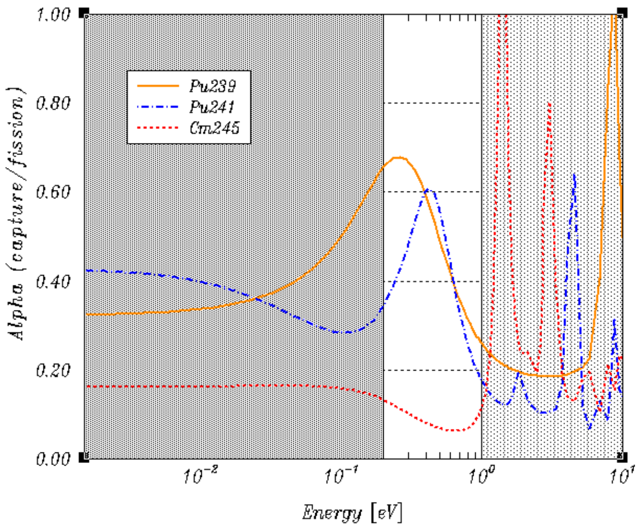


Figure 9: Ratio between capture to fission for different fissile isotopes

5.3. Influence of the DRIVER particle size

An illustration of the influence of the DRIVER particle size on the fuel element $k_{infinity}$ and average fuel element mass flow is given in Figure 10 and Figure 11. Due to the spatial self shielding effect, the increase of the DRIVER coated fuel particle size allows to increase the fuel element $k_{infinity}$. Furthermore, it enhances the thermal fission in the DRIVER kernel. As a consequence, the plutonium consumption is larger (+ 3 % at 420 GWd/t). This weak influence observed on plutonium consumption is much more larger on the americium and curium production (+ 10 % at 420 GWd/t when the kernel radius increases from 100 to 300 µm).

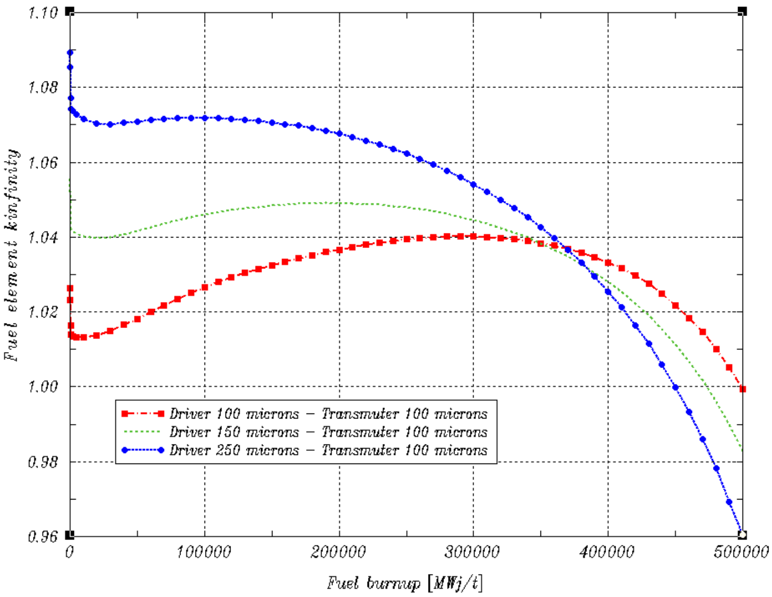


Figure 10: Fuel element $k_{infinity}$ during fuel depletion

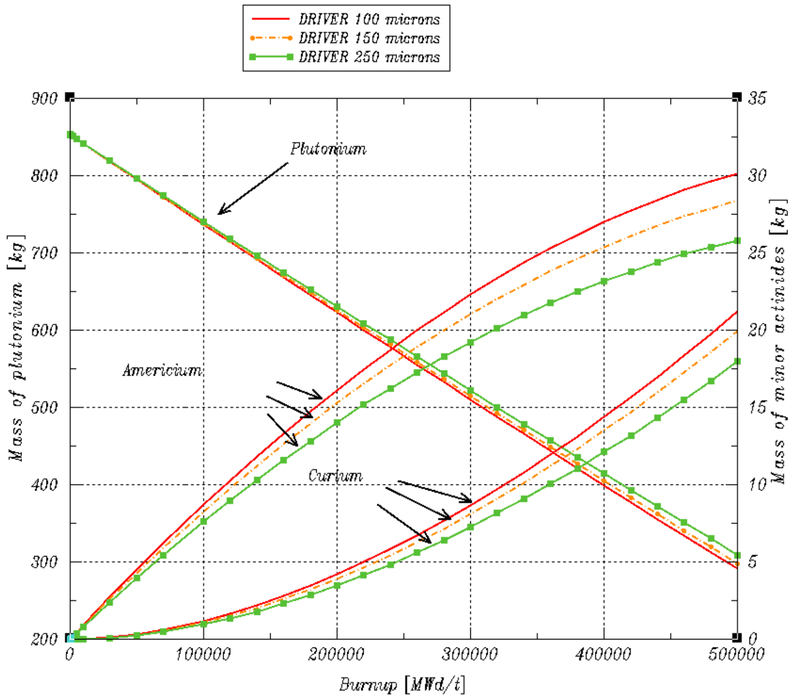
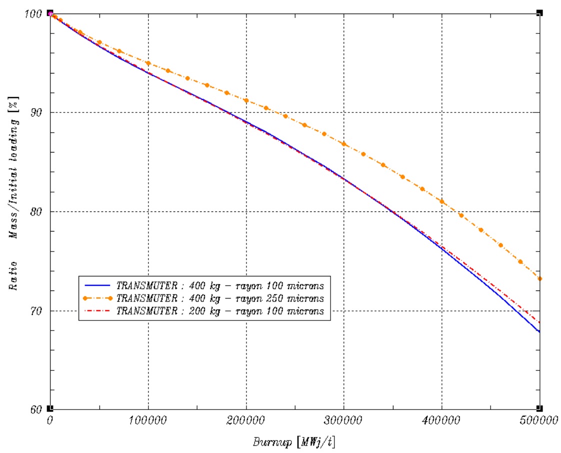
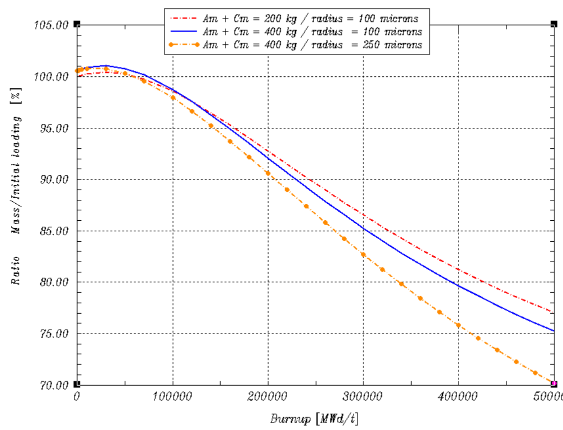


Figure 11: Influence of the DRIVER particle size on the fuel element mass flow

5.4. Influence of both TRANSMUTER particle size and TRANSMUTER mass

The influence of both TRANSMUTER particle size and TRANSMUTER mass are indicated in Figure 12. As far as the TRANSMUTER fuel is concerned, it must be said that the TRANSMUTER consumption is enhanced when the kernel size decreases and the TRANSMUTER mass increases. In the first case, the small kernel size favours the neutron epithermal captures in the minor actinides loaded in the TRANSMUTER fuel. In the second case, the increase of the TRANSMUTER mass induces a spectrum hardening that also favours the minor actinides consumption





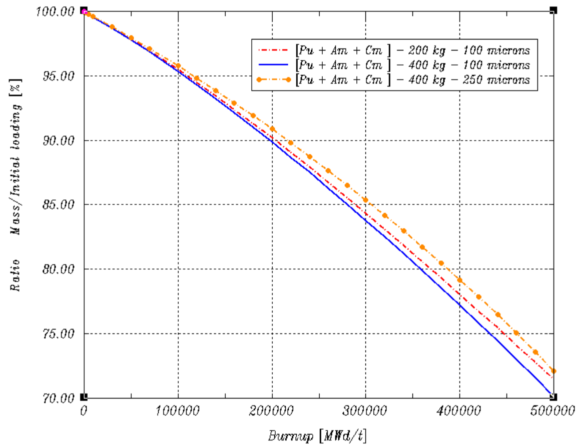


Figure 12: Impact of TRANSMUTER characteristics on fuel element TRANSMUTER mass flow

6. PRELIMINARY ESTIMATION OF THE MASS BALANCE - ONCE THROUGH FUEL CYCLE

From the previous configuration ($M_{Core\ Driver}$ = 900 kg - ϕ_{Driver} = 600 µm | $M_{Core\ Transmuter}$ = 400 kg - $\phi_{Transmuter}$ = 200 µm), the transmutation rate has been evaluated from the fuel element calculation in infinite medium. After three-years critical [2], in the DRIVER coated fuel particles, the ratio $[Pu + Am + Cm]_{Discharged}$ / Pu_{Loaded} is roughly 40 %. In the TRANSMUTER fuel, the ratio $[Pu + Am + Cm]_{Discharged}$ / $[Pu + Am + Cm]_{Loaded}$ is roughly 75 % to 80 %.

As to conclude, using two types of coated fuel particles in the Deep-Burn concept allows to reach a **consumption rate of roughly 60 % in the DRIVER fuel** (the DRIVER fuel is loaded with first generation plutonium) and a **consumption rate of 25 to 30 % in the TRANSMUTER fuel** (loaded with DRIVER fuel that has not been used in a previous irradiation and minor actinides coming from LWR irradiated fuel).

7. PRELIMINARY ESTIMATION OF THE MASS BALANCE – MULTIRECYCLING OF PLUTONIUM AND MINOR ACTINIDES

7.1. Description of the multirecycling process

In the previous analyses, the mass balance (both DRIVER and TRANSMUTER) was evaluated considering a once-through fuel cycle. The objective of the analysis presented in this section was to evaluate the capabilities of multirecycling both plutonium and minor actinides in the same reactor. The calculation was performed using a modified fuel element geometry. In this configuration, the standard fuel element contains 180 DRIVER fuel rods and 36 TRANSMUTER fuel rods (the ratio DRIVER to TRANSMUTER is equal to 5 instead of 2 in the previous section).

The major difference in the multirecycling analysis discussed hereafter concerns the coated fuel particles composition. During the first fuel cycle, the DRIVER coated fuel particles are entirely loaded with first generation plutonium coming from Ligth Water Reactor spent fuel. As far as the TRANSMUTER particles are concerned, they are loaded with the minor actinides discharged from the LWR fuel assembly.

At the end of the first fuel cycle and after a cooling period of 5 years, all the spent plutonium coming from the DRIVER fuel is extracted (with a loss of 0,1 % during the recycling process) and mixed with "fresh plutonium" (this "fresh plutonium" comes from LWR spent fuel) in order to feed the DRIVER particles. Following the fuel fabrication, 2 years of storage are taken into account before the beginning of the fuel irradiation in core.

In order to achieve a constant fuel cycle length of 300 EFPD (three batches fuel management), the mass of “fresh plutonium” is adjusted at the beginning of each cycle. Moreover, all the minor actinides are recovered from the DRIVER and TRANSMUTER particles (with a loss of 1 % during the recycling process) and loaded in the TRANSMUTER coated fuel particles with the same duration for cooling and storage.

For the analysis, three different hypotheses have been analysed concerning the recycling of minor actinides.

Scenario ► : *In the first case, the total mass of minor actinides loaded into the core is kept constant*. This hypothesis implies that the mass of minor actinides coming from spent LWR fuel assembly is adapted at the beginning of each fuel cycle in order to keep the total mass constant.

Scenario ► : In the second case, the mass of minor actinides coming from LWR spent fuel assembly is kept constant. As a consequence, during the multirecycling process, the mass of minor actinides loaded into the core at the beginning of each cycle increases.

Scenario ► : In the third scenario, the total mass of minor actinides loaded into the core is kept constant (as in the first scenario). The change concerns the fuel cycle length. Different configurations with a modified fuel cycle length (200, 250 and 300 EFPD) and their impact on the scenario are assessed.

7.2. First scenario: results and comments

All the results concerning the first scenario are gathered in Table I. The analyses were performed for three different minor actinides loading (100, 150 and 200 kg). In any cases and whatever the mass of minor actinides loaded into the core is, the multirecycling process must be stopped after the third cycle because the total mass of minor actinides discharged from the core is higher than the initial criteria fixed for the analysis.

Loading minor actinides in the fuel element induces a diminution of the plutonium consumption in term of plutonium mass balance. However, the plutonium mass balance normalised to the total energy produced (given in kg/TWhe) is constant and roughly equal to –95 kg/Twhe. Furthermore, the increase of the minor actinides loading induces an increase of the americium consumption in the TRANSMUTER fuel but a decrease of the americium consumption in the DRIVER fuel. As far as the curium is concerned, the discharged mass increases whatever the total mass of minor actinides loaded into the core is.

To conclude, the minor actinides transmutation rate increases with the minor actinides mass loaded into the core. Furthermore, it induces a diminution of the plutonium consumption. In any cases, the multirecycling process is limited by the total mass of minor actinides discharged from the core.

		The fuel cycle length is kept constant = 300 EFPD The minor actinides Core loading is kept constant and equal to: 100 kg		150 kg		200 kg		
Fuel Cycle N°		1	2	1	2	1	2	3
Core INPUT								
DRIVER	Pu	859,18	1005,94	888,80	1022,08	938,18	1060,14	1060,14
	Am	9,57	12,51	9,90	13,42	10,45	14,91	14,52
TRANSMUTER	Am	88,49	61,76	132,73	97,38	176,97	133,89	104,58
	Cm	10,74	35,87	16,10	49,40	21,47	62,11	89,91
Total Minor Actinides		108,80	110,14	158,73	160,20	208,89	210,91	209,01
Core OUTPUT								
DRIVER	Pu	281,83	397,24	312,29	417,81	365,93	456,00	485,58
	Am	42,72	63,60	47,38	67,14	54,46	73,31	75,89
	Cm	15,44	25,64	15,72	25,61	15,73	25,49	28,02
TRANSMUTER	Am	13,57	13,71	22,27	20,71	34,18	29,14	26,77
	Cm	22,43	40,66	33,74	55,94	45,03	70,57	87,35
Fuel Cycle Length	[EFPD]	299,10	301,90	300,30	303,30	297,08	305,08	287,34
Pu balance	kg	-577,35	-608,70	-576,51	-604,27	-572,25	-604,14	-574,56
Pu balance	%	**-67,20**	**-60,51**	**-64,86**	**-59,12**	**-61,00**	**-56,99**	**-54,20**
Pu balance	kg/TWhe	**-94,40**	**-98,60**	**-93,89**	**-97,43**	**-94,20**	**-96,84**	**-97,79**
Pu composition	Pu238	8,08	9,07	7,94	9,35	7,51	9,53	10,20
(discharged fuel element)	Pu239	4,91	4,24	6,90	5,19	10,49	6,85	5,21
	Pu240	32,55	25,94	32,82	26,33	32,88	26,90	22,92
	Pu241	17,01	14,91	19,07	16,41	21,20	18,45	15,00
	Pu242	37,45	45,84	33,27	42,72	27,92	38,27	46,66
DRIVER Am balance	kg	33,15	51,09	37,48	53,72	44,01	58,40	61,37
TRANSMUTER Am balance	kg	-74,92	-48,05	-110,46	-76,67	-142,79	-104,75	-77,81
TOTAL Am balance	kg	**-41,77**	**3,04**	**-72,98**	**-22,95**	**-98,78**	**-46,35**	**-16,44**
TOTAL Am balance	%	-42,60	4,09	-51,17	-20,71	-52,71	-31,15	-13,80
TOTAL Am balance	kg/Twhe	**-6,83**	**0,49**	**-11,88**	**-3,70**	**-16,26**	**-7,43**	**-2,80**
Am composition	Am241	34,41	28,65	38,00	31,29	43,23	35,60	28,83
(discharged fuel element)	Am242	0,19	0,14	0,28	0,19	0,42	0,28	0,19
	Am243	65,4	71,21	61,72	68,52	56,35	64,11	70,98
DRIVER Cm balance	kg	15,44	25,64	15,72	25,61	15,73	25,49	28,02
TRANSMUTER Cm balance	kg	11,69	4,79	17,64	6,54	23,56	8,46	-2,56
TOTAL Cm balance	kg	**27,13**	**30,43**	**33,36**	**32,15**	**39,29**	**33,95**	**25,46**
TOTAL Cm balance	%	252,61	84,83	207,20	65,08	183,00	54,66	28,32
TOTAL Cm balance	kg/Twhe	**4,44**	**4,93**	**5,43**	**5,18**	**6,47**	**5,44**	**4,33**
Cm composition	Cm242	0,01	*	0,01	*	0,01	0,01	*
(discharged fuel element)	Cm243	1,18	0,48	1,27	0,58	1,35	0,67	0,40
	Cm244	86,72	84,74	85,07	83,05	83,35	81,25	80,23
	Cm245	8,79	9,58	10,37	10,90	12,26	12,68	11,36
	Cm246	3,21	4,97	3,19	5,23	2,95	5,15	7,53
	Cm247	0,07	0,17	0,08	0,19	0,07	0,20	0,35
	Cm248	0,01	0,05	0,01	0,05	0,01	0,05	0,13
Minor Actinides balance	kg	**-14,64**	**33,47**	**-39,62**	**9,20**	**-59,49**	**-12,40**	**9,02**
Minor Actinides balance	kg/Twhe	**-2,39**	**5,42**	**-6,45**	**1,48**	**-9,79**	**-1,99**	**1,54**

Table I: First scenario – The fuel cycle length and the total mass of minor actinides loaded into the core are constant

7.3. Second scenario: results and comments

In the second scenario, the increase of the minor actinides mass loaded into the core at the beginning of each cycle allows to solve the problem that occurred in the first scenario. Different configurations have been analysed depending on the mass of minor actinides coming from the LWR spent fuel assembly.

In all assessed cases, the multirecycling process must be stopped: the increase of the minor actinides mass induces a decrease of the reactivity margin at the beginnig of cycle

that can not be compensate by an increase of the plutonium loading (increase of "fresh plutonium" loading).

		The fuel cycle length is kept constant = 300 EFPD The mass of minor actinides mass coming from LWR is kept constant								
		▶ Total MA at first cycle = 100 kg ▶ MA from LWR = 50 kg			▶ Total MA at first cycle = 100 kg ▶ MA from LWR = 30 kg			▶ Total MA at first cycle = 50 kg ▶ MA from LWR = 50 kg		
Fuel Cycle N°		1	2	3	1	2	3	1	2	3
Core INPUT										
DRIVER	Pu	859,18	1079,24	1283,87	859,18	1039,28	1206,1	842,85	1093,14	1309,44
	Am	9,57	13,32	16,53	9,57	12,88	15,04	9,39	12,68	16,64
TRANSMUTER	Am	88,49	100,01	136,88	88,49	82,32	110,9	44,24	88,44	134,52
	Cm	10,74	40,51	78,3	10,74	38,36	70,8	5,37	30,50	71,31
Total Minor Actinides		108,80	153,84	231,71	108,80	133,56	196,74	59,00	131,62	222,47
Core OUTPUT										
DRIVER	Pu	281,83	447,25	630,4	281,83	419,73	558,6	251,46	445,90	651,8
	Am	42,72	72,63	100,75	42,72	67,77	90,51	38,60	73,01	103,56
	Cm	15,44	27,41	33,42	15,44	26,51	33,35	15,94	28,58	33,68
TRANSMUTER	Am	13,57	20,87	35,12	13,57	17,37	27,17	6,01	18,10	35,2
	Cm	22,43	50,93	87,91	22,43	46,11	77,68	11,19	42,31	83,16
Fuel Cycle Length	[EFPD]	299,08	312,90	313	299,08	307,50	313,3	303,00	317,00	312,1
Pu balance	kg	-577,35	-631,99	-653,47	-577,35	-619,55	-647,50	-591,39	-647,24	-657,64
Pu balance	%	**-67,20**	**-58,56**	**-50,90**	**-67,20**	**-59,61**	**-53,69**	**-70,17**	**-59,21**	**-50,22**
Pu balance	kg/TWhe	**-94,41**	**-98,78**	**-102,10**	**-94,41**	**-98,53**	**-101,07**	**-95,45**	**-99,85**	**-103,05**
Pu composition (discharged fuel element)	Pu238	8,08	9,06	9,34	8,08	9,10	9,48	8,21	8,83	9,07
	Pu239	4,91	6,14	9,73	4,91	5,08	7,17	3,13	5,93	10,31
	Pu240	32,55	26,57	24,23	32,55	26,26	23,55	31,10	26,26	24,33
	Pu241	17,01	17,40	18,79	17,01	16,15	17,08	14,20	16,99	18,94
	Pu242	37,45	40,82	37,91	37,45	43,41	42,72	43,42	41,99	37,36
DRIVER Am balance	kg	33,15	59,31	84,22	33,15	54,89	75,47	29,21	60,33	86,92
TRANSM Am balance	kg	-74,92	-79,14	-101,76	-74,92	-64,95	-83,73	-38,23	-70,34	-99,32
TOTAL Am balance	kg	**-41,77**	**-19,83**	**-17,54**	**-41,77**	**-10,06**	**-8,26**	**-9,02**	**-10,01**	**-12,40**
TOTAL Am balance	%	-42,60	-17,50	-11,43	-42,60	-10,57	-6,56	-16,82	-9,90	-8,20
TOTAL Am balance	kg/Twhe	**-6,83**	**-3,10**	**-2,74**	**-6,83**	**-1,60**	**-1,29**	**-1,46**	**-1,54**	**-1,94**
Am composition (discharged fuel element)	Am241	34,41	33,56	37,78	34,41	31,00	33,15	29,23	32,76	38,43
	Am242	0,19	0,22	0,36	0,20	0,20	0,25	0,12	0,20	0,37
	Am243	65,40	66,21	61,87	65,40	68,82	66,60	70,66	67,03	61,20
DRIVER Cm balance	kg	15,44	27,41	33,42	15,44	26,51	33,35	15,94	28,58	33,68
TRANSMUTER Cm balance	kg	11,69	10,42	9,61	11,69	7,75	6,88	5,82	11,81	11,85
TOTAL Cm balance	kg	**27,13**	**37,83**	**43,03**	**27,13**	**34,26**	**40,23**	**21,76**	**40,39**	**45,53**
TOTAL Cm balance	%	252,61	93,38	54,96	252,61	89,31	56,82	405,21	132,43	63,85
TOTAL Cm balance	kg/Twhe	**4,44**	**5,91**	**6,72**	**4,44**	**5,45**	**6,28**	**3,51**	**6,23**	**7,13**
Cm composition (discharged fuel element)	Cm242	0,01	0,01	*	0,01	*	*	0,01	0,01	*
	Cm243	1,18	0,61	0,49	1,18	0,55	0,42	1,01	0,59	0,49
	Cm244	86,72	82,94	78,58	86,72	83,84	80,08	88,90	83,88	79,04
	Cm245	8,79	11,68	14,98	8,79	10,63	13,18	6,98	11,36	15,18
	Cm246	3,21	4,56	5,59	3,21	4,77	5,95	3,03	4,01	4,98
	Cm247	0,07	0,16	0,27	0,07	0,17	0,28	0,06	0,13	0,23
	Cm248	0,01	0,04	0,09	0,01	0,05	0,10	0,01	0,03	0,07
Minor Actinides balance	kg	**-14,64**	**18,00**	**25,49**	**-14,64**	**24,20**	**31,97**	**12,74**	**30,38**	**33,13**
Minor Actinides balance	kg/Twhe	**-2,39**	**2,81**	**3,98**	**-2,39**	**3,85**	**4,99**	**2,06**	**4,69**	**5,19**

Table II: Second scenario – The fuel cycle length and the mass of minor actinides coming from the LWR spent fuel assembly are constant

7.4. Third scenario: results and comments

In the third scenario, the total mass of minor actinides loaded into the core is constant during the multirecycling process. Three fuel cycle length have been analysed, 200, 250 and 300 EFPD. The obtained results are gathered in Table III.

The decrease of the fuel cycle length induces a decrease of americium and curium consumption (by decreasing the fuel cycle length, the plutonium discharged from the core is characterized by a higher content in fissile isotopes and less Pu^{242}). However, we faced the same problem as in the first scenario. After the fourth recycling, the total mass of minor actinides discharged from the core is higher than the mass of minor actinides fixed as constant parameter.

		The minor actinides Core loading is kept constant									
		Total minor actinides loading = 200 kg									
		Fuel Cycle Length = 300 EFPD			Fuel Cycle Length = 250 EFPD			Fuel Cycle Length = 200 EFPD			
Fuel Cycle N°		1	2	3	1	2	3	1	2	3	4
Core INPUT											
DRIVER	Pu	938,18	1060,14	1060,14	827,08	971,56	971,19	721,47	837,25	912,52	912,77
	Am	10,45	14,91	14,52	9,21	13,61	13,67	8,04	11,75	13,01	12,57
TRANSMUTER	Am	176,97	133,89	104,58	176,97	139,83	113,12	176,97	146,40	125,89	110,6
	Cm	21,47	62,11	89,91	21,47	56,49	81,79	21,47	50,26	69,69	84,19
Total Minor Actinides		208,89	210,91	209,01	207,65	209,93	208,58	206,48	208,41	208,59	207,36
Core OUTPUT											
DRIVER	Pu	365,93	456,00	485,58	355,81	449,51	477,18	352,54	448,01	489,78	511,6
	Am	54,46	73,31	75,89	47,24	66,57	68,97	40,27	56,15	64,68	65,21
TRANSMUTER	Cm	15,73	25,49	28,02	10,69	18,93	20,87	6,47	10,36	14,54	15
	Am	34,18	29,14	26,77	41,59	34,91	32,27	53,02	48,02	40,93	39,61
	Cm	45,03	70,57	87,35	43,31	67,23	82,71	40,59	61,57	75,02	84,74
Fuel Cycle Length	[EFPD]	297,08	305,08	287,34	245,00	263,00	247,3	191,30	195,51	209,82	197,3
Pu balance	kg	-572,25	-604,14	-574,56	-471,27	-522,05	-494,01	-368,93	-389,24	-422,74	-401,17
Pu balance	%	-61,00	-56,99	-54,20	-56,98	-53,73	-50,87	-51,14	-46,49	-46,33	-43,95
Pu balance	kg/TWhe	-94,20	-96,84	-97,79	-94,07	-97,07	-97,69	-94,31	-97,36	-98,53	-99,44
Pu composition (discharged fuel element)	Pu238				6,66	8,59	9,43	5,78	7,25	8,34	8,75
	Pu239				12,48	7,93	5,94	16,22	10,86	8,11	6,91
	Pu240				35,38	29,85	25,70	37,35	34,12	29,95	26,92
	Pu241				20,50	18,87	15,69	19,47	18,89	17,33	15,23
	Pu242				24,97	34,77	43,23	21,19	28,89	36,27	42,20
DRIVER Am balance	kg	44,01	58,40	61,37	38,03	52,96	55,30	32,23	44,40	51,67	52,64
TRANSM Am balance	kg	-142,79	-104,75	-77,81	-135,38	-104,92	-80,85	-123,95	-98,38	-84,96	-70,99
TOTAL Am balance	kg	-98,78	-46,35	-16,44	-97,35	-51,96	-25,55	-91,72	-53,98	-33,29	-18,35
TOTAL Am balance	%	-52,71	-31,15	-13,80	-52,29	-33,86	-20,15	-49,58	-34,13	-23,97	-14,90
TOTAL Am balance	kg/Twhe	-16,26	-7,43	-2,80	-19,43	-9,66	-5,05	-23,45	-13,50	-7,76	-4,55
Am composition (discharged fuel element)	Am241				45,14	38,10	31,54	48,31	42,71	37,44	33,07
	Am242				0,50	0,33	0,23	0,62	0,46	0,34	0,27
	Am243				54,37	61,57	68,22	51,06	56,82	62,22	66,67
DRIVER Cm balance	kg	15,73	25,49	28,02	10,69	18,93	20,87	6,47	10,36	14,54	15,00
TRANSMUTER Cm balance	kg	23,56	8,46	-2,56	21,84	10,74	0,92	19,12	11,31	5,33	0,55
TOTAL Cm balance	kg	39,29	33,95	25,46	32,53	29,67	21,79	25,59	21,67	19,87	15,55
TOTAL Cm balance	%	183,00	54,66	28,32	151,51	52,52	26,64	119,19	43,12	28,51	18,47
TOTAL Cm balance	kg/Twhe	6,47	5,44	4,33	6,49	5,52	4,31	6,54	5,42	4,63	3,85
Cm composition (discharged fuel element)	Cm242				0,02	0,01	*	0,02	0,01	0,01	*
	Cm243				1,57	0,83	0,52	1,79	1,09	0,72	0,52
	Cm244				84,18	82,02	81,04	84,95	82,99	81,53	80,52
	Cm245				11,55	12,40	11,34	10,96	12,03	12,00	11,24
	Cm246				2,61	4,54	6,71	2,23	3,73	5,47	7,26
	Cm247				0,06	0,16	0,29	0,05	0,12	0,22	0,33
	Cm248				0,01	0,04	0,10	0,01	0,02	0,06	0,12
Minor Actinides balance	kg	-59,49	-12,40	9,02	-64,82	-22,29	-3,76	-66,13	-32,31	-13,42	-2,80
Minor Actinides balance	kg/Twhe	-9,79	-1,99	1,54	-12,94	-4,14	-0,74	-16,91	-8,08	-3,13	-0,69

Table III: Third scenario – The total mass of minor actinides loaded into the core is constant – Variation of the fuel cycle length

7.5. Preliminary conclusion

From the preliminary results obtained with different assessed scenarios, no major positive trends have been identified for the plutonium and minor actinides multirecycling. After four fuel cycle, the curium mass balance is still positive. Nevertheless, further analyses are needed in order to evaluate the reliability of the concept. The impact of the used calculation methods on the fuel balance must be also evaluated.

8. CONSIDERATIONS ABOUT THE GLOBAL TRANSMUTATION RATE CALCULATION

Preliminary results indicates good relatively high incerneration rates and good destruction capacity of block-type ractor. However, it turns out that the transuranic mass balances in a such a reactor cannot be estimated easily from only fuel element calculations in infinite medium.

Indeed, in the case of GT-MHR core design and due to a large migration area of 410 cm^2 (the graphite thermal capture is very low), many neutrons escape the active core and are slowed in the reflector, before going back to the core. The neutron balance in the core is largely modified because of the reflectors, and finally, the core $k_{effective}$ is greater than the $k_{infinity}$ calculated in infinite medium (when passing from assembly calculations to core calculations, the reactivity increase due to a better thermal utility factor and larger resonance escape probability factor is not compensated by leakages). This is also of first importance on the Pu^{240} transmutation into Pu^{241}, because the probability for neutrons to escape the large 1 eV resonance of Pu^{240} is greater when reflectors are described.

Figure 13 gives an overview of how far neutron flux in the active core is disturbed by reflectors [5]. In order to illustrate the phenomena, the core has been divided into different radial zones, each radial zone having a thickness of 10 cm. The first zone (zone 1) is located near the internal reflector while zone 4 is roughly located in the center of the core. Neutron fluxes, calculated at different locations in the core by the Monte-Carlo code TRIPOLI4 [6], are compared to neutron spectrum calculated by APOLLO2 for a single assembly in infinite medium.

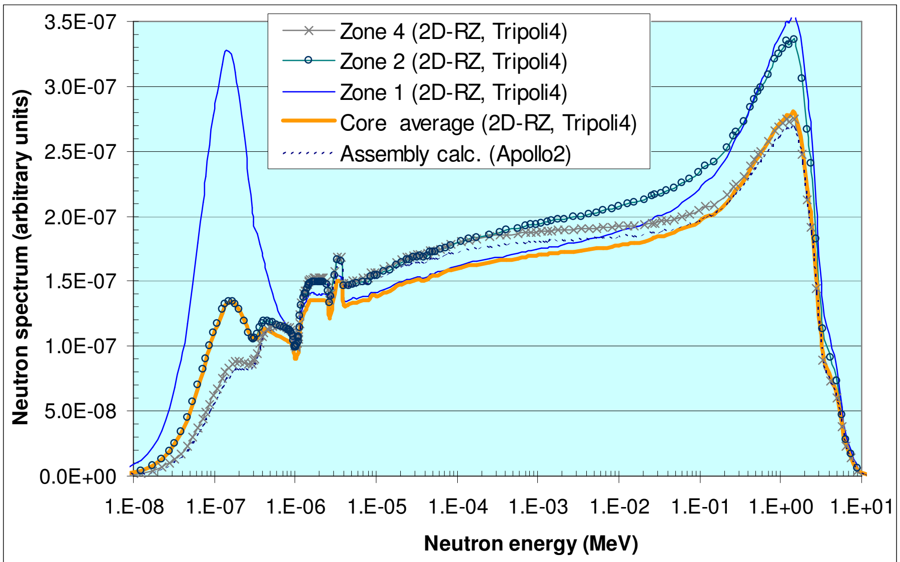


Figure 13: Neutron spectrum in different core zones compared to assembly calculations

In the concern of simplicity, only a few regions are plotted. In zone 1 close to the reflector, the thermal component (< 1eV) reach 19% of the total flux, whereas it is 11% in case of the average core and only 8,3% in infinite medium. In zone 2, deeper in the core, the neutron spectrum behaves as the core average. In the center part of the core (plotted as zone 4), the neutron spectrum follows the fundamental zone very well. In fact, for an annular core of 80 cm in thickness, the 40 cm inner part of fuel is well represented by the fundamental mode.

The transmutation rate of isotope depends on the fuel location in the core due to the difference between neutron spectra. Figure 14 shows the core average concentration of Pu^{241} calculated on a simplified 2D-RZ geometry with the diffusion code CRONOS2 [7], but also results for zone 1 and zone 4 issued from the same calculation.

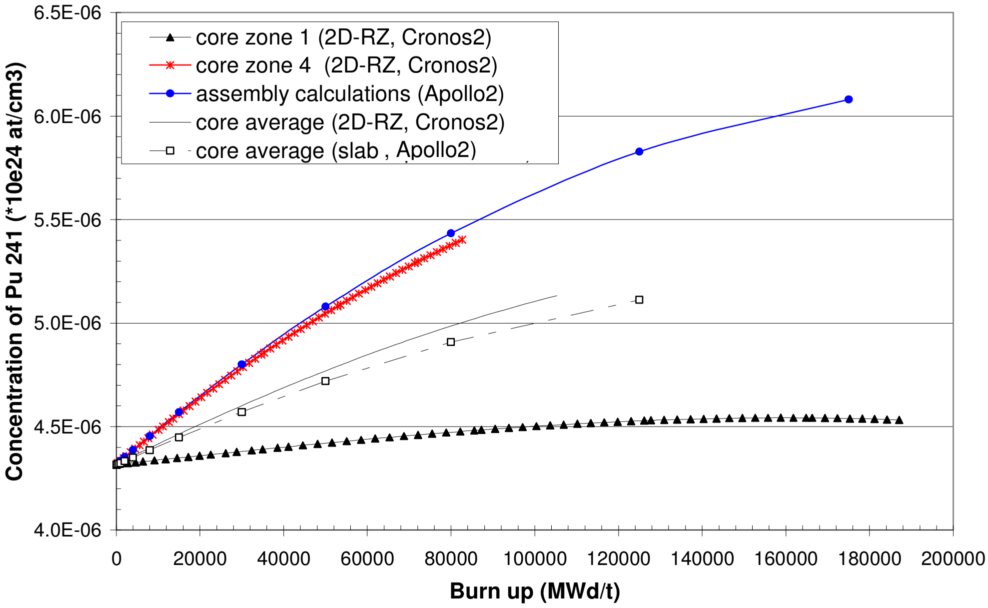


Figure 14: Pu^{241} concentration as a function of burn-up

These results indicate that the change of the core $k_{effective}$ and the isotopic concentration are strongly dependant to the core design and cannot be calculated accurately using assembly calculations.

9. CONCLUSION

Destruction of transuranic waste discharged from LWR is the subject of a significant analysis effort. Following a GENERAL ATOMICS proposal for a deep burn concept, CEA has defined a specific modelling in order to evaluate in a proper way the performances. This document presented preliminary physical analysis based on a fuel element containing high amounts of transuranic isotopes

In term of performances, preliminary results show sensitivity of the maximum BU to the reactivity balance. Moreover, fuel back end cycle studies in PWR are usually tackled on the basis of a fuel assembly model. These calculations performed in infinite medium and based on the fundamental mode hypothesis, allow reaching rapidly the fuel mass balance avoiding core calculations. In this paper, information is provided with regard to the precautions that must be taken in transuranic cycle studies carried out on annular core configurations as the one encountered in the GT-MHR. It turns out that the transuranic mass balances in a GT-MHR cannot be estimated easily from fuel element calculations but rather need the use of a core modelling approach taking into account the presence of the graphite reflectors.

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