ENHANCEMENT OF ACTINIDE INCINERATION AND TRANSMUTATION RATES IN ADS EAP-80 REACTOR CORE WITH MOX PUO_2&UO_2 FUEL

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Abstract

Neutronics calculations of the accelerator driven reactor core EAP-80 with UO_2&PuO_2 MOX fuel elements and Pb-Bi coolant are presented in this paper. Monte Carlo optimisation computations of several schemes of the EAP-80 core with different types of fuel assemblies containing burnable absorber B_4C or H_2Zr zirconium hydride moderator were performed with the purpose to enhance the plutonium and actinide incineration rate. In the first scheme the reactor core contains burnable absorber B_4C arranged in the cladding of fuel elements with high enrichment of plutonium (up to 45%). In the second scheme H_2Zr zirconium hydride moderated zones were located in fuel elements with low enrichment (~20%). In both schemes the incineration rate of plutonium is about two times higher than in the reference EAP-80 core and at the same time the power density distribution remains significantly unchanged compared to the reference core. A hybrid core containing two fuel zones one of which is the inner fuel region with UO_2&PuO_2 high enrichment plutonium fuel and the second one is the outer region with fuel elements containing zyrconium hydride layer was also considered. Evolution of neutronics parameters and actinide transmutation rates during the fuel burn-up is presented. Calculations were performed using the MCNP-4B code and the SCALE 4.3 computational system.

1. Introduction

In the last years there is an increased interest to the problem of burning-up of plutonium and minor actinides generated from waste and dismantled weapons. A project of an accelerator driven sub-critical reactor prototype EAP-80 is considered in Italy. In the ANSALDO technical reports a detailed description of the reference core configuration for the accelerator driven sub-critical demonstration facility is given [1]. Preliminary neutronics analysis of an accelerator driven sub-critical energy amplifier prototype (EAP-80) was presented in the Atzeni report [2]. The main purpose of project [2] was to demonstrate the soundness of the basic principles of the energy amplifier [3] with U-Pu MOX fuel which is similar to the fuel used in the super Phenix fast reactor. A lead-bismuth eutectic is used as a neutron production target and also as a coolant. Neutron producing target located in the centre of the reactor core is irradiated by 600 MeV proton beam. Due to the low value of neutron absorption cross-sections on lead-bismuth eutectic a low gradient of neutron flux may be obtained in the reactor core that leads to a small value of the power peaking factor. Optimisation calculations of neutronics parameters of the reference core of the EAP-80 were performed in ANSALDO and ENEA. The fuel composition used in the reference reactor core is presented in Table 1.

Table 1. **Fuel composition (10^{24} cm^{-3})**

	Atomic density		**Atomic density**		**Atomic density**
^{234}U	7.673302×10^{-7}	^{237}Np	1.056298×10^{-6}	^{241}Pu	1.390316×10^{-4}
^{235}U	9.345065×10^{-5}	^{238}Pu	1.468511×10^{-5}	^{242}Pu	6.823877×10^{-5}
^{236}U	8.919691×10^{-7}	^{239}Pu	3.715382×10^{-3}	^{241}Am	1.235840×10^{-4}
^{238}U	1.774578×10^{-2}	^{240}Pu	1.307362×10^{-3}	^{16}O	4.642046×10^{-2}

The reference core contains fuel assemblies with plutonium enrichment of 23.2%. The arrangement of fuel assemblies in the reference reactor core is shown in Figure 1.

2. Calculation method

The effective multiplication factor, power density distribution and the reaction rates for the reactor core were computed by the MCNP-4b [4] code with DLC-181, DLC-189 (ENDF/B-6) cross-section libraries at the temperature of 300 K. Calculations of fuel burn-up were performed using the ORIGENS module and the SCALE 4.3 [5] computational system. Problem dependent cross-sections for the burn-up computations for the considered reactor core were prepared using the NITAWL and XSDRNPM modules in the SCALE system. The effective multiplication factor k_{eff} for the reference core at a temperature of T = 300K is equal to 0.9839 ± 0.0005. In the present computations the temperature of the reactor core was taken equal to 300 K in order to compare the results of optimisation calculations with the parameters of the reference core. The fuel in the reference core has a high concentration of ^{238}U that leads to plutonium breeding reaction competitive with the burning-up reaction on plutonium. We will define a plutonium burn-up rate as a sum of fission and capture rates on ^{239}Pu and a subtraction of breeding rate of ^{239}Pu in the reaction (n,γ) of neutron capture on ^{238}U**:**

$$B_{Pu} = m \times \int_V \int_0^{20MeV} \left[\Sigma_f^{239}(E) + \Sigma_C^{239}(E) - \Sigma_C^{238}(E)\right] \Phi(r,E)\ dE\ dV$$

Here $\Sigma_{f,C}(E)$ are the fission and capture cross-sections, $\Phi(r,E)$ is the neutron flux, and B_{Pu} is a plutonium burning rate in units of kg per full power year (kg/FPY), and *m* is a normalisation parameter used to take into account the reactor power. Supposing that a spatial distribution of fission events in the reactor core with fission neutron source is the same as in the core with a spallation neutron source (i.e. in the core with k_{eff} near criticality), we can estimate the B_{Pu} from the criticality calculations. Calculations with a spallation neutron source located in the centre of the reactor core are also presented. The spectrum and the mean energy E_s of evaporated neutrons in spallation reaction was calculated by us using the medium energy code SITHA [6]. For the considered target it is equal to E_s = 3.3 MeV. The total factor of neutron multiplication in the core with the spallation neutron source was calculated using the formula

$$M_{tot} = 1 + \iint \Phi(r,E) \sum_i \rho_i \nu^i_{fis} \sigma^i_{fis}(E) dE\ dV + \iint \Phi(r,E) \sum_i \rho_i x^i \sigma^i_{n,xn}(E) dE\ dV$$

For the reference core M_{tot}=50.9, the neutron source multiplication factor is equal to $k_s = (M_{tot} - 1)/M_{tot} = 0.98$. The current of proton beam I_p = 1.67 mA is obtained for the reactor power P_r = 80 MW_{th}. Plutonium burn-up rate in the reference core is equal to B_{Pu} = 13.4 kg/FPY and B_{Pu} = 13.7 kg/FPY for fission and external neutron sources respectively at the reactor power P_r = 80 MW. A spatial distribution of power density in the fuel elements was calculated using the space distribution of fission events in fuel assemblies (heating by photons in the present calculations was not taken in account due to the small values compared with the fission reactions). Power peaking factor, $k_v = k_r k_z$, in the reference core with fission source is equal to 1.37 in the assembly near the spallation neutron target. It should be noted that the spatial distribution of heating energy in the reactor core calculated using the fission neutron source differs from the energy distribution in the core calculated with the spallation neutron source. The radial peaking factor k_r is increased to k_r = 1.27 compared to the value k_r = 1.20 obtained for the fission neutron source. This difference depends on the sub-critical level of the core and for the core with lower value of k_{eff} this difference will be greater. Above mentioned phenomenon plays an important role in the dependence of the reactor power distribution and power peaking factors versus the changing of the k_{eff} parameter during the reactor fuel cycle.

In order to enhance the plutonium incineration rate we propose to shift the neutron spectrum in the fuel into the energy region where the ratio of fission cross section on ^{239}Pu to capture cross-section on ^{238}U is greater than in the reference core. At the same time the effective multiplication factor k_{eff} should be equal to or less than the value 0.984. Below we consider several ways of how to enhance the burning rate of plutonium in the reactor core.

3. Core with burnable absorber B_4C in fuel elements

Application of thin axial burnable absorbers B_4C in the gap between the fuel pellet and the stainless steel cladding allows to increase the plutonium enrichment and to obtain hard neutron spectrum in the core. Due to the neutron absorption on ^{10}B in the resonance energy region the rate of capture reaction on ^{238}U reduces and the ratio of fission to capture cross-sections for transuranium nuclides increases. The fuel pellet with plutonium enrichment 43.7%, has a central hole r_{fuel} = 0.100 cm and the outer radius of fuel pellet is equal to R_{fuel} = 0.347 cm. The thickness of $^{10}B_4C$ layer is equal to 0.013 cm. The average power density in fuel pellets in this scheme at the beginning of fuel cycle (BOC) is equal to q_f = 24 W/g and is comparable with the reference value of power density (q_f = 22 W/g in the reference fuel pellets). The plutonium ^{239}Pu burning rate is equal to B_{Pu} = 25 kg/FPY, i.e. about two times higher than the plutonium burn-up in the reference core (B_{Pu} = 13.7 kg/FPY).

4. Core with zirconium hydride in fuel elements

For enhancement of plutonium burn-up rate a moderated zone containing zirconium hydride in the fuel element may be used. Zirconium hydride is a good moderator and has good inert properties. Application of zirconium hydride moderated zones in fast reactors were considered in papers [8-9].

We have considered the reactor core with fuel elements containing zirconium hydride layer located in the gap between the fuel pellet and steel cladding or around the steel cladding. All dimensions of the fuel pin were taken as in the reference core. Due to the shifting of the neutron spectrum to the thermal energy region more than 70% of the plutonium burn-up events occurs in the thermal energy region. The use of the fuel elements with zirconium hydride and plutonium enrichment of 20%-23% permits to burn up about B_{Pu} = 25 kg/FPY (at the P_r = 80 MW) of plutonium at the average power density in the fuel of q_f = 227 W/cc. There are two possible arrangements of zirconium hydride layer in fuel element: (1) HZr arranged abutting to the outer surface of the steel cladding, and (2) HZr layer may be arranged in the gap between the fuel pellet and the steel cladding of the fuel element.

In Table 2 results of computations of the reactor core with different arrangement of HZr layer in fuel element are presented. Burn-up rate of plutonium in fuel elements with HZr layer (Δd_2(HZr) ≈ 0.045 ÷ 0.072 cm) arranged abutting to the outer surface of fuel pin is equal to B_{Pu} = 24.8 kg/FPY, while B_{Pu} = 21.6 kg/FPY in the core with HZr layer (Δd_1(HZr) ≈ 0.035 cm) arranged inside the fuel element. The average power density is equal to q_f = 228 W/cc (21.8 W/g) in fuel elements with HZr layer arranged abutting to the outer diameter of fuel cladding, and q_f = 258W/cc (24.7 W/g) in fuel elements containing HZr layer inside fuel element.

Table 2**. Fuel elements containing H_2Zr cladding arranged in different positions:**
(1) Abutting to the outer diameter of the steel cladding.
(2) In the gap between the fuel pellet and the steel cladding.

	Plutonium enrichment, %			
Parameter	**23.225% Reference core**	**20.0%**	**23.2%**	**55%**
Position of HZr	–	(1)	(2)	(1) (2)
r_{fuel}, cm	0.09	0.09	0.08	0.09
R_{fuel}, cm	0.357	0.357	0.33	0.301
r_{clad}, cm	0.3685	0.3685	0.3685	0.3685
R_{clad}, cm	0.425	0.425	0.425	0.425
k_{eff}	0.9839(5)	0.9831(5)	0.9811(6)	0.9828(6)
k_s	0.980	0.982	0.981	0.984
I_p (mA)	1.67	1.51	1.61	1.41
q_f(W/g)	21.98	21.82	24.73	31.00
$k_v = q_{max}/q_f$	1.35	1.37	1.32	–
B_{Pu}, (kg/FPY)	13.7	24.8	21.6	33.2

Fuel element with plutonium enrichment 55% and two moderated zones of zirconium hydride is also considered. The first HZr zone is arranged abutting to the outer diameter of fuel element (the thickness of the layer is equal to 0.07 cm) and the second zone is arranged in the gap between the fuel pellet and the steel cladding. In order for the effective multiplication factor to be equal to k_{eff} = 0.984, a small fraction (3%) of natural Eu absorber was added to internal zirconium hydride layer. In this scheme the plutonium incineration rate is equal to B_{Pu} = 33.2 kg/PFY (P_r = 80 MW) and the average power density in the fuel is equal 31.0 W/g.

5. Production of ^{210}Po from ^{209}Bi in the cores with B_4C and zirconium hydride

Production of ^{210}Po in the lead-bismuth eutectic was calculated for the reference core in the ENEA report [8]. It was indicated that the main contribution to the production of ^{210}Po give neutrons with energy below 20 MeV in the reaction of neutron capture:

$$^{209}\mathrm{Bi}(n,\gamma)\rightarrow{}^{210g}\mathrm{Bi}(T_{1/2} = 5.013 \text{ days})\rightarrow{}^{210}\mathrm{Po}$$

The fraction α_{210g} of the cross-section value for ^{210g}Bi in the total (n,γ) cross-section of ^{209}Bi according to the report [8] is equal to α_{210g} = 0.72. Here we present the results of depression of ^{210}Po production in the ADS reactor with fuel elements containing burnable absorber $^{10}B_4C$ or zirconium hydride. Calculations were performed using the MCNP-4b code for heterogeneous model of the reactor with detailed description of fuel assemblies and the spallation neutron production target. The cross-section of radiative capture (n,γ) on ^{209}Bi used in MCNP-4b is shown in Figure 3. In order to estimate the amount of produced ^{210}Po we use the value α_{210g} = 0.72 from the report [8]. The reaction rate (n,γ) on ^{209}Bi was calculated for different parts of the reactor and is 1.5 times lower for the core with B_4C, and 3.3 times lower for the core with H_2Zr compared to the reference core. The amount of ^{210}Po produced in Pb-Bi eutectic in the reference scheme is equal to 3.6 kg/FPY.

6. Hybrid core with reference FA and FA containing zirconium hydride zones

A hybrid core contains two zones with reference fuel assemblies and a small fraction of fuel assemblies with zirconium hydride. We will consider three schemes of arrangement of fuel assemblies in the reactor core:

- (C1) in the first scheme the inner fuel zone (3-5 rings of hexagons in the core) contains reference FA and the outer zone (6-7 rings of hexagons) contains fuel elements with HZr cladding (see Figure 2).
- (C2) fuel assemblies with HZr are arranged in 7-8 rings of hexagons so that a thick layer of Pb-Bi eutectics is located between the inner fuel zone and the outer fuel zone.
- (C3) fuel assemblies with HZr layer are arranged in a scattered order in the core containing reference fuel assemblies.

In all above schemes the number of fuel assemblies containing HZr is equal to 48 and their fraction is equal to 40% from the total number of fuel assemblies in the reactor core. In Table 3 main parameters for the hybrid cores are presented. For comparison the parameters of the reference core and of the core containing FA with HZr are also shown.

Figure1. **Reference reactor core**

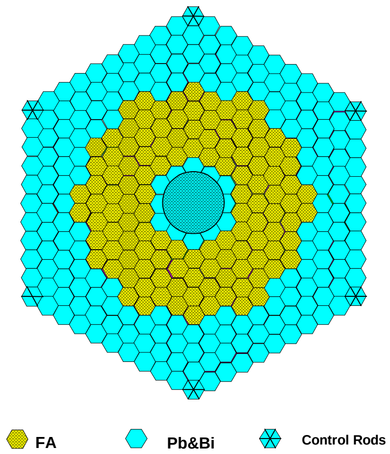
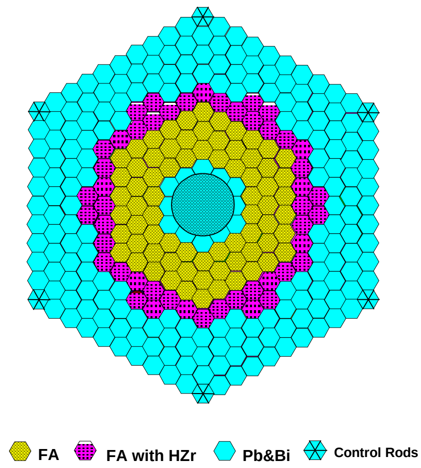


Figure 2. **Hybrid core with FA containing HZr**



C1 CORE. In the core C1 the total amount of ^{239}Pu burn-up is equal to $B_{Pu} = 21$ kg/PFY (12.7 kg/PFY in the reference, and $B_{Pu} = 8.4$ kg/PFY in the FA with HZr). The radial peaking factor is equal to $k_r = 1.20$ and is comparable with the value for the reference core. The neutron flux averaged over the reference fuel assemblies in the core C1 is equal $\Phi^n_{fuel} = 6.5 \times 10^{14}$ cm^{-2}s^{-1}, and in fuel assemblies with HZr cladding the flux is equal to $\Phi^n_{fuel} = 2.9 \times 10^{14}$ cm^{-2}s^{-1}. The flux averaged over all fuel assemblies in the core C1 is equal to $\Phi^n_{fuel} = 5.0 \times 10^{14}$ cm^{-2}s^{-1}. The production of ^{210}Po in (n,γ) reaction on ^{209}Bi in region of dummy assemblies and in heat transfer regions is equal to 0.0088 (n,γ) reactions per one fission neutron which is about 3 times less than in the corresponding zones of the reference core.

C2 CORE. The main parameters for the core C2 is presented in Table 3. The amount of ^{239}Pu burn-up is equal to $B_{Pu} = 20.6$ kg/PFY. However the radial peaking factor $k_r = 1.28$. In order to decrease the k_r and to flatten the power density distribution, the enrichment in the inner fuel zone should be increased while in the outer zone containing FA with HZr cladding should be decreased below 10%. The amount of produced ^{210}Po in dummy assemblies and in heat transfer regions is equal to 0.013 (n,γ) reactions per fission neutron, which is 2.02 times less than the production of ^{210}Po in the same zones of the reference core.

C3 CORE. In this core 48 fuel assemblies with HZr layer have plutonium enrichment of 10% and arranged in a scatter order in the reactor core. In Table 3 the parameters for this core are presented.

Table 3.**Neutronics parameters of hybrid two zones core containing reference FA and FA with HZr layer calculated at BOC using the MCNP-4b code.**

Type of core	**Reference**	**FA with HZr**	**(C1)**	**(C1)**	**(C2)**	**(C3)**
(mean enrich.)	23.2%	20.0%	25.0%	23.2%	20.0%	20.0%
Reference FA Number of FA Enrichment ,%	120 23.2	0	72 29.6	72 20	72 26.6	72 26.6
FA with HZr Number of FA Enrichment ,%	0	48 20	48 18	48 28	48 10	48 10
Hex rings of FA with HZr	–	3-7	6-7	6-7	7-8 6-dummy	3-7
Burn-up ^{239}Pu, B_{Pu9} (kg/FPY)	14.3	24.8	12.66 (Ref.) 8.40 (HZr) 21.1	3.30 (Ref.) 22.2 (HZr) 25.5	9.73 (Ref.) 10.83 (HZr) 20.6	13.51 (Ref.) 7.07 (HZr) 20.6
q_f, (W×cm^{-3})	216	217	216	216	215	209
k_r	1.20	1.19	1.20	1.80	1.28	1.17
Φ^{n}_{fuel}, (n cm^{-2} s^{-1})	8.5×10^{14}	3.2×10^{14}	6.5×10^{14} (Ref.) 2.9×10^{14} (HZr) 5.0×10^{14} (Av.)	4.1×10^{14} (Ref.) 3.4×10^{14} (HZr) 3.8×10^{14} (Av.)	6.3×10^{14} (Ref.) 2.8×10^{14} (HZr) 4.9×10^{14} (Av.)	–
E^{n}_{fuel} (MeV)	0.430	0.650	0.518 (Ref.) 0.572 (HZr) 0.530 (Av.)		0.466 (Ref.) 0.566 (HZr) 0.489 (Av.)	
^{210}Po, per 1 fiss. n	0.0263	0.0078	0.0088	–	0.0130	0.0110
k_{eff}	0.9839(5)	0.9831(5)	0.9852(6)	0.9824(5)	0.9802(6)	0.9812(9)

7. Comparison of incineration parameters for the reference core, for the core with fuel elements containing B_4C or zirconium hydride

The main parameters of the reference core and of the core containing $^{10}B_4C$ absorbing zone, or zirconium hydride moderator zone are presented in Table 4. The effective multiplication factor calculated using the MCNP-4b code with cross-section library DLC-181 (T = 300 K) for the core with B_4C is equal to $k_{eff} = 0.9833 \pm 0.0005$, and for the core with zirconium hydride $k_{eff} = 0.9831 \pm 0.0006$. The average power density in the fuel pellets with B_4C is equal to q_f = 22 W/g (235 W/cc), and in the core with H_2Zr - q_f = 21.8 W/g (227 W/cc). The power peaking factors for the cores with $^{10}B_4C$, H_2Zr and for the reference core are equal to 1.33, 1.37 and 1.35 respectively. So, these parameters are very close to the values in the reference core, but the plutonium burn-up rate at the BOC in fuel elements with B_4C, H_2Zr is about two times higher compared to the reference core: 25 kg/FPY compared to 13.7 kg/FPY.

Table 4. **Comparison of burn-up parameters of the reference EAP-80 core and the core containing FA with burnable absorbers or moderated zones**

	Reference core	**FA with B_4C clad**	**FA with ZrH_2 matrix**
Enrichment	23.2%	43.7%	20.0%
r_{fuel}, cm	0.09	0.1	0.09
R_{fuel}, cm	0.357	0.347	0.357
r_{clad}, cm	0.3685	0.3685	0.3685
R_{clad}, cm	0.425	0.425	0.425
k_{eff}	0.9839(5)	0.9833(6)	0.9831(6)
k_s	0.980	0.982	0.982
I_p (mA)	1.67	1.51	1.51
q_f(W/g)	21.98	22.60	21.82
$k_v = q_{max}/q_l$	1.35	1.37	1.37
Φ^n_{fuel} (cm^{-2}s^{-1})	8.5×10^{14}	5.8×10^{14}	3.2×10^{14}
E^n_{fuel} (MeV)	0.43	0.60	0.65
B_{Pu9} (kg/FPY)	13.7	25.0	24.8

The comparison of neutron spectra Φ_n averaged over all fuel pellets in the reference core, in the core with B_4C and in the core with zirconium hydride is presented in Figure 3. It is seen that B_4C absorber and zirconium hydride reduce the fraction of neutrons absorbed in (n,γ) reaction on ^{238}U in resonance region, and zirconium hydride moreover shifts the neutron spectrum to the thermal energy region.

The average energy E^n_{fuel} of neutron spectrum (calculated using fission neutron source) in fuel pellets with B_4C is equal to E^n_{fuel} = 0.60 MeV, while in the reference core E^n_{fuel} = 0.43 MeV. Neutron fluxes ϕ^n_{fuel} in fuel pellets at the reactor power P_r = 80 MW are equal respectively to 8.5×10^{14}, 5.8×10^{14} and 3.2×10^{14} (cm^{-2}s^{-1}) for the reference fuel pellets, for fuel elements with B_4C and with zirconium hydride. The energy dependence of integrated plutonium burn-up rate (i.e. integrated over thin energy interval and over all fuel elements) for the thermal energy region is shown in Figure 4 for the reference core, for the core with B_4C and with zirconium hydride. In Table 5 we present the fractions of plutonium incineration rate in 6 energy intervals: $0 - 10^{-4}$ MeV, $10^{-4} - 10^{-3}$ MeV, $10^{-3} - 10^{-2}$ MeV, $10^{-2} - 10^{-1}$ MeV, $10^{-1} - 1$ MeV and $1 - 10$ MeV. In fuel elements with B_4C absorber the plutonium is burning in the fast energy region, while the plutonium is burning mainly in the thermal energy region in FA with zirconium hydride. In the fast and thermal energy regions the ratio of fission cross section of ^{239}Pu to the capture cross-section for ^{238}U is high.

Figure 3. **Neutron spectra averaged over fuel pins in the reference core, in FA with B_4C, and in Fa with H_2Zr. Neutron cross-section in the reaction $^{209}Bi(n,\gamma)$ is also shown**

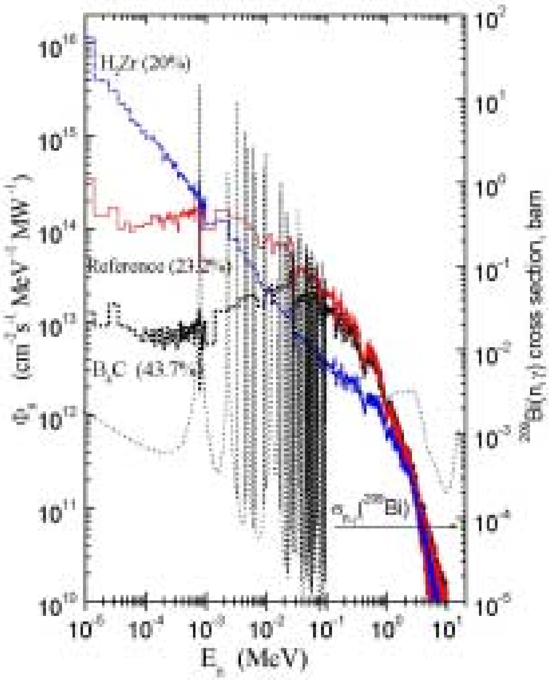


Figure 4. **Energy distribution of plutonium burn-up in the reference core, in FA with B_4C, and in FA with HZr**

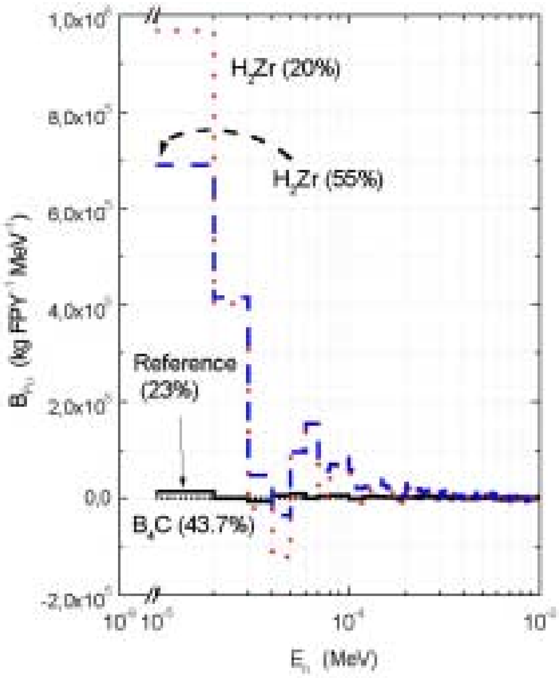


Table 5. **Energy dependence of $B_{Pu,}$ plutonium burn-up rate (%) versus the neutron energy in the ADS EAP-80 in different cores containing: reference fuel elements, fuel elements with thin B_4C cladding, Fuel elements with H_2Zr matrix**.

Here $B_{Pu}(E_{i-1},E_i) = m\int_{Ei-1}^{Ei}\left[\Sigma_f^{239}(E)+\Sigma_C^{239}(E)-\Sigma_C^{238}(E)\right]\Phi(E)dE$.

Neutron energy (MeV)	Energy dependence of plutonium $B_{Pu}(E_{i-1},E_i)$ burn-up, %		
(E_{i-1},E_i)	Reference core. Enrichment 23.2%	Core with B_4C cladding. Enrichment 45.0%	Core with ZrH_2 matrix. Enrichment 20.0%
$0 – 10^{-4}$	3.78%	0.284%	71.10%
$10^{-4} – 10^{-3}$	9.78%	0.73%	14.66%
$10^{-3} – 10^{-2}$	8.89%	4.06%	1.08%
$10^{-2} – 10^{-1}$	4.74%	19.47%	0.00%
$10^{-1} – 1$	54.81%	56.39%	6.87%
1 – 10	18.0%	19.07%	6.29%
B_{Pu}, (kg/FPY)	13.7	25.2	24.8

8. Power distribution in the reference core, in the core with B_4C, H_2Zr

8.1 Reference core

Power density distribution in the fuel elements was calculated using the spatial distribution of fission events in fuel assemblies (photon heating in the present calculations was not taken in account due to the small value compared to the fission reactions). The axial power peaking factor was calculated as a ratio of fission energy in the axial layer to the average fission energy in the fuel assembly where the axial layer is located. The radial power peaking factor was calculated as the ratio of the fission energy in each fuel assembly to the energy averaged over all fuel elements. The spatial distribution of energy in the reactor core with the fission neutron source differs from the energy distribution in the core with spallation neutron source. This difference depends on the level of the core sub-criticality and for the core with k_{eff} close to 1.0 this difference will be very small. However, the changing of the parameter k_{eff} to the higher sub-criticality during the burning of fissile ^{239}Pu will increase the difference in power peaking factors calculated for the cores with the fission source and with the spallation neutron source. For the reference core with the fission source $k_v = 1.37$ ($k_{eff} = 0.984$) and $k_v = 1.45$ for the spallation neutron source.

8.2 Fuel elements with B_4C cladding

The radial peaking factor calculated for the core with the spallation neutron source is equal to $k_v = 1.47$ while in the core with fission source the maximal value of power peaking factor is equal to the value of $k_v = 1.37$. The average power density in the fuel is equal to $q_f = 235 \pm$ W/cc ($q_f = 244 \pm 12$ W/cc for the spallation source), that is comparable with the reference power density $q_f = 229 \pm 12$ W/cc.

8.3 Fuel elements with zirconium hydride cladding

The average power density in fuel elements with H_2Zr cladding arranged abutting to the outer surface of fuel element and with plutonium enrichment of 20% is equal $q_f = 227 \pm 12$ W/cc, and the maximal value of the peaking factor is equal to $k_v = 1.35$. The power density distribution in fuel elements with the internal zirconium hydride cladding and plutonium enrichment of 23.2% has increased slightly because of lower volume of fuel and is equal to $q_f = 258 \pm 12$ W/cc and the maximal value of the peaking factor is equal to $k_v = 1.32$.

9. Fuel depletion and actinide transmutation

Time evolution of fuel composition and calculation of actinide transmutation rate in fuel cycle were performed using the ORIGENS module of the SCALE 4.3 computational system. Problem dependent effective cross-section for all nuclides in the fuel were prepared using the COUPLE, NITAWL and XSDRNPM modules in the SCALE system. The reactor power was taken equal to 80 MW. Time dependent nuclear concentrations of actinides and of fission products were used in MCNP-4b Monte Carlo computation of changing the effective multiplication factor, neutron multiplicity factor and of the reaction rates in the fuel during the fuel irradiation.

The transmutation rate of actinides is defined as the fractional difference in the final mass of the actinides (Pu, Am, Cu) and the initial mass of actinides. Transmutation rate for all actinides calculated after 1 FPY of the fuel irradiation in the Reference Core is equal to -1.4%, in the core containing FA with B_4C cladding is equal to -2.0%, and in the core with FA with zirconium hydride cladding -2.3%. In the hybrid two-zones reactor core the transmutation rate is equal to -2.2%.

In Table 6 the mass of actinides at the BOC and after 1 FPY of fuel irradiation, as well as the burn-up rate B_{Pu} (kg/FPY) for ^{239}Pu, are presented for different compositions of the reactor core:

Table 6. **Mass of actinides in the BOC and after 1 FPY of fuel irradiation in the reference core, in the core containing FA with B_4C, and FA with HZr.**

Time	**T = 0 (BOC)**				**T = 360 days**			
Core (Enr., %)	Reference (23.2%)	B_4C (43.7%)	HZr (24%)	Hybrid (23.2%)	Reference (23.2%)	B_4C (43.7%)	HZr (24%)	Hybrid (23.2)
^{239}Pu, kg	519.7	908.2	539.1	560.7	506.7	884.3	513.8	539.4
B_{Pu}, kg	0	0	0	0	-13.0	-23.9	-25.3	-21.3
^{241}Pu, kg	19.6	34.2	20.3	21.2	19.5	32.8	25.3	23.5
^{241}Am, kg	17.4	30.4	18.1	18.8	17.6	31.6	16.5	18.5
Pu, Am, Cu, kg	750.0	1311.3	778.0	809.3	739.8	1284.8	759.9	791.3

The burn-up rate of ^{239}Pu in FA with $^{10}B_4C$ or HZr is about two times higher than in the reference core. It should be noted that the burn-up rates of ^{239}Pu calculated using the MCNP-4b reaction rates (see Table 4) are slightly different from results in the above table, because we supposed that reaction rates remain constant during the time of irradiation. In the core with $^{10}B_4C$ the burn-up rate of ^{241}Pu is about -1.4 kg/FPY, while in the core with HZr the mass of ^{241}Pu is increased by 5 kg/FPY. The amount of ^{241}Am in the reference core is increased by 0.2 kg/FPY, in the core with $^{10}B_4C$ is increased by 1.2 kg/FPY, while in the core with HZr the amount is reduced by -1.6 kg/FPY, or by -0.3 kg/FPY in the hybrid core.

It should be noted that the effective cross-section of ^{10}B in FA with $^{10}B_4C$ is about 1.6 barn, and the maximum of the neutron spectrum is located in the energy region higher then 0.1 MeV. So, the burning of $^{10}B_4C$ cladding in the fuel element during fuel cycle is small. Nevertheless, the burning of $^{10}B_4C$ cladding was taken into account in the MCNP calculations. Production of fission fragments is comparable in all considered schemes of the reactor core: 0.002 kg of ^{135}Xe, 0.1 kg of ^{149}Sm, 1.0 kg of ^{137}Cs, 0.7 kg of ^{99}Tc, 0.2 kg of ^{129}I per 1 FPY. The effective absorption cross-section of ^{135}Xe in fuel elements with HZr is three orders of magnitude lower than in the thermal power reactors and is about 1 800 barns, and samarium ^{149}Sm has effective cross-section of absorption equal to 80 barns. In calculations of reactivity loss during the fuel cycle the presence of all fission fragments were taken into account. Reactivity calculations were performed using the MCNP-4b code. In the reference core the reactivity loss $\Delta\rho$ during 1 FPY is equal to $\Delta\rho = -1.6\%$/FPY, in the core with HZr zone $\Delta\rho = -2.0\%$/FPY, in the hybrid core with HZr $\Delta\rho = -1.8\%$/FPY, while in the core with $^{10}B_4C$ $\Delta\rho = -1.1$ %/FPY.

The dependence of proton beam current on k_{eff} may be estimated using the simple formula:

$$P_r = I_p \frac{k_{eff} M_{n,xn}}{(1 - k_{eff})\, \nu_f} \times N_{n/p} \varepsilon_f ,$$

where P_r is the reactor power, I_p is the proton beam current, k_{eff} is the effective multiplication factor, $N_{n/p}$ is the multiplicity of spallation neutrons in Pb-Bi target irradiated by protons, ε_f = 190 MeV, ν_f is the average number of neutrons per fission event, $M_{n,xn}$ multiplication factor taking into account non-fission multiplication reactions (n,xn) for primary spallation neutron. If we assume that the reactor power is constant during the reactor company, and that $N_{n/p}$ also does not depend on time then the dependence of proton beam current I_p(T) on k_{eff} may be estimated as

$$I_p(T) = I_p(0)\frac{k_{eff}(0)(1-k_{eff}(T))}{k_{eff}(T)(1-k_{eff}(0))},$$

where I_p(0) is the proton beam current and k_{eff} (0) is the effective multiplication factor at the beginning of the reactor company. Using the values of reactivity loss Δρ and T = 1FPY we may estimate the ratio $I_p(T)/I_p(0)$. For the reference core $I_p(T)/I_p(0)$ = 2.0, and for the core containing FA with $^{10}B_4C$ $I_p(T)/I_p(0)$ = 1.6.

10. Conclusion

Application of a thin cladding of burnable absorber B_4C or a thin zone containing hydride zirconium moderator in the PuO_2&UO_2 MOX fuel element of the EAP-80 accelerator driven reactor prototype permits considerably to increase the plutonium burn-up rate. Incineration of ^{239}Pu in FA with B_4C or with HZr is about 25 kg/FPY at the reactor core power of P_r = 80 MW_{th} which is about 2 times greater compared to the reference core. Plutonium enrichment in fuel elements with B_4C cladding was chosen to be 43.7%. In the core containing fuel elements with zirconium hydride a fuel with plutonium enrichment of 20-23% is used. The geometry of the reactor core and of fuel assemblies in the proposed schemes was unchanged and remains the same as in the reference core. A hybrid core containing reference fuel elements in the inner region of the core and fuel elements with zirconium hydride cladding in the outer region of the core was considered. A reactor core with scattered arrangement of fuel assemblies with HZr is also considered. The fraction of fuel elements with zirconium hydride cladding in the hybrid cores was equal to 40% from the total number of fuel elements loaded into the core. The average power density in fuel with B_4C or with H_2Zr and in hybrid cores at the beginning of fuel cycle is comparable with the power density in the Reference Core and is equal to q_f = 224 W/cc, q_f = 227 W/cc and q_f = 215 ÷ 217 W/cc, respectively. The power peaking factor in these cores remains the same as in the reference core and is equal to k_v = 1.37 (for exception of one hybrid scheme). The dependence of main neutronic, actinide and FP transmutation characteristics for different core models during time of irradiation has been calculated. The transmutation rates for ^{239}Pu, ^{241}Am and for total actinides is maximum for the core with fuel elements containing zirconium hydride cladding. The transmutation rate of ^{241}Pu is maximal in the core with fuel elements having B_4C cladding. The reactivity loss during time of irradiation is minimal in the core containing fuel elements with the cladding of B_4C burnable absorber.

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REFERENCES

[1] ANSALDO Technical Reports for the Reactor Core of the ADS Demonstration Facility, 1999-2000.

[2] S. Atzeni, *Preliminary Neutronics Analysis of the Energy Amplifier Prototype*, 1998, Report EA D2.02 4 407.

[3] C. Rubbia *et al.*, *Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier*, CERN/AT/95-44 (ET), 1995.

[4] T. Wakabayashi, *Status of Transmutation Studies in a Fast Reactor at JNC. Actinide and Fission Product Partitioning and Transmutation*. Proc. of the 5th Int. Inform. Exch. Meeting on Actinide and Fission Product Partitioning and Transmutation, Mol,Belgium, 1998, EUR 18898 EN, OECD/NEA (Nuclear Energy Agency), Paris, France, 1999.

[5] Judith F. Breismeister, *MCNP – A General Monte Carlo N-Particle Transport Code*, LA-12625-M.

[6] *The SCALE 4.3 Computational System.*

[7] A.V. Daniel, V.Yu. Petrov, E.A. Sokolov, *Program SITHA*, Communication of the Joint Institute for Nuclear Research, 1991, Dubna.

[8] W. Hongchun, T. Takeda. *Minor Actinides Incineration By Loading Moderated Targets in Fast Reactor*, Proc. of Int. Conf. Mathematics and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications, Madrid, 1999, p. 580-586.

[9] Hongchun Wu, Diasuke Sato, Toshikazu Takeda. *Minor Actinides Incineration By Loading Moderated Targets in Fast Reactor*, Journal of Nuclear Science and Technology, 2000, Vol. 37, No. 4, p. 380-386.

[10] T. Sanda, K. Fujumura, K. Kobayashi, K. Kawashima, M. Yamawaki, K. Konashi, *Fast Reactor Core Concepts for Minor Actinides Transmutation Using Hybrid Fuel Targets*, Journal of Nuclear Science and Technology, 2000, Vol. 37, No. 4, p. 335-343.

[11] A.Yu. Konobeev, M. Vecchi, *Nuclide Composition of Pb-Bi Heat Transfer Irradiated in 80 MW Sub-critical Reactor*, ENEA Activity Report, 1999, Workshop on Spallation Module.