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Reactor with metallic fuel and lead-208 coolant

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Abstract

This time, several projects dedicated to fast reactors (FRs) with lead and lead-bismuth coolants, BREST-OD-300, SVBR-100, RBETS-M, BRUTs are proposed in Russia. They will have several valuable consuming properties: chemical inertness, low neutron absorption, low activation and others. Usage of lead coolant leads also to the possibility of achieving a hard-enough neutron spectrum that allows increasing the incineration probability of ^{241}Am, ^{237}Np and other low fissile actinides. High power FRs have large-sized cores that limits the value of neutron energy by the value of 0.5 MeV, which is insufficient for incineration of above mentioned actinides. Small and medium power reactors have smaller cores and, respectively, have harder neutron spectra. Usage of lead and low moderating innovative fuel allow further increasing neutron energy to the value inquired for low fissile actinides incineration.In the paper a possibility of obtaining a neutron spectrum with the average value of neutron energy higher than 0.5 MeV is considered. It is performed in the frame of the project of BRUTs series reactors, i.e. small power LFRs proposed in the Obninsk Institute for Nuclear Power Engineering. A scope for achieving a hard neutron spectrum in the reactor BRUTs-25 core of small sizes, DxH = 0.5x0.4 m^2, is shown. Findings are that in the core fueled with Pu-Am-Np-Zr alloy and cooled with enriched lead, ^{208}Pb, the average value of neutron energy, $<E_n>$, is high-enough, about 0.95 MeV, as well as the share of fast neutron, $E_n>0.8$ MeV, in the neutron spectrum is very high, about 40%. In such of conditions, ^{241}Am and ^{237}Np incineration probabilities in the core center are higher than 50% and values of their one-group fission cross-sections are higher than 0.7 barn. This circumstance allows burning 15-**16**wt% of low fissile isotopes for one campaign of BRUTs-25. The presence of ^{241}Am in the fuel, in a quantity of 28.7 kg, allows transmuting about **8.6** kg of its mass for one reactor campaign that lasts about 3 years (1000 effective days). It means that to transmute the quantity of ^{241}Am produced by the VVER-1000 for one year, equal to 25.8 kg, it will be needed about 3 BRUTs-25 type low power reactors operating for 1000 effective days.

Keywords: fast reactor; metallic fuel; lead-208; transmuting of minor actinides, hard neutron spectrum.

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1. Introduction

Currently, for promising fast reactors, along with light sodium coolant, heavy lead-bismuth and lead coolants are considered. The advantages of the latter include their chemical inertness, low activation and low neutron absorption [1-3]. However, another useful property of heavy coolants - the ability to slightly slow down neutrons, apparently, is not given due attention. As is known, the weak neutron moderation by lead is due to its large atomic mass, A = 207.2, and the presence in its composition, in the amount of 52%, of a stable isotope of lead ^{208}Pb with a high threshold of inelastic neutron scattering, E = 2.63 MeV. Previously, the authors of [4–11] pointed out the possibility of increasing the average neutron energy by 6–7% in the inner subzone of the RBEC-M medium-power reactor [12] when replacing its standard lead-bismuth coolant with lead enriched in ^{208}Pb isotope. The article shows that the coolant from lead enriched in the ^{208}Pb isotope, in combination with a slightly slowing metal fuel, for example, plutonium-americium-neptunium [13, 14], and small core sizes, $D\text{x}H \approx 0.50 \times 0.42$ m^2, can provide an extremely high average neutron energy in the center of the core close to 1 MeV, i.e. the value unattainable in the current operating fast sodium reactors of medium power BOR-60, BN-600 and BN-800 [15]. A reactor with extremely hard neutrons can be used for various purposes, first of all, for burning environmentally hazardous minor actinides, ^{237}Np, ^{241}Am and ^{244}Cm, with a high nuclear fission threshold, $E_{\text{threshold}} > 0.8$ MeV, as well as for studying radiation damage in materials of nuclear engineering that are known to occur mainly due to exposure with fast neutrons. The paper considers the possibility of obtaining a hard neutron spectrum in a reactor of low power, 25 MW thermal, but with parameters sufficient for a noticeable, about 15%, burnout of low fissile nuclides during one campaign of the reactor. It is assumed that the duration of the reactor campaign is limited only by the set of neutron fluence, at which catastrophic damage to the cladding of the fuel elements does not occur.

2. BRUTs-25 reactor concept

Designs of BRUTs series reactors were considered in [16-19]. Their optimization and transfer to the regime of a more efficient burner reactor, BRUTs-25, consisted in increasing the thermal power and using innovative plutonium-americium-neptunium fuel doped with zirconium [14]. The design parameters of the BRUTs-25 reactor are given in table 1.

Table 1.. Design parameters of the BRUTs-25

Parameter	Value
Thermal capacity, MW	25
Equivalent core diameter, mm	500
Core height, mm	418
Number of FAs in core	7
Fuel	$Pu_{эн}47{,}6+Am10{,}5+Np0{,}3+Zr41{,}6$
Coolant	^{208}Pb
Core inlet/outlet coolant temperature, °C	450 / 530
Fuel cladding surface temperature, °C	610
Coolant/fuel/structural material volume fraction, %	69 / 25 / 6
Core fuel load weight, kg	215.8
Pu power-grade weight, kg	102.7
^{241}Am weight, kg	28.7
^{237}Np weight, kg	0.8
Density of neutron flux in the core, cm^{-2}·s^{-1}	$2{,}6 \cdot 10^{15}$

3. Calculation technique

The neutron flux densities in the center of the BRUTs-25 core were calculated using the MCNP/4B program [20]. Based on them and when using nuclear constants prepared [21] from the ENDF/B-VII.0 library, the following neutron and physical parameters were calculated: average neutron energy in the center of the core; fraction of hard, $E_n > 0.8$ MeV, neutrons; one-group cross sections for fission and radiation neutron capture of $^{238\text{-}242}$Pu, ^{241}Am and ^{237}Np nuclei and the probability of fission of these nuclei.

4. Calculation results

In table 2 results of calculation of several actinides cross sections in conditions of the BRUTs-25 hard neutron spectrum are given.

Table 2 Several actinides cross sections in the BRUTs-25 hard neutron spectrum

Parameter	Value
Average energy of neutrons in the core center, MeV	0.955
Fraction of hard neutrons, En>0.8 MeV, %	40.28
^{241}Am one-group fission cross section, barn	0.731
^{241}Am one-group capture cross section, barn	0.708
^{241}Am fission probability, %	50.81
^{237}Np one-group fission cross section, barn	0.821
^{237}Np one-group capture cross section, barn	0.540
^{237}Np fission probability, %	60.30
^{238}Pu one-group fission cross section, barn	1.516
^{238}Pu one-group capture cross section, barn	0.298
^{238}Pu fission probability, %	83.56
^{239}Pu one-group fission cross section, barn	1.684
^{239}Pu one-group capture cross section, barn	0.128
^{239}Pu fission probability, %	92.95
^{240}Pu one-group fission cross section, barn	0.836
^{240}Pu one-group capture cross section, barn	0.178
^{240}Pu fission probability, %	82.45
^{241}Pu one-group fission cross section, barn	1.754
^{241}Pu one-group capture cross section, barn	0.174
^{241}Pu fission probability, %	90.98
^{242}Pu one-group fission cross section, barn	0.670
^{242}Pu one-group capture cross section, barn	0.155
^{242}Pu fission probability, %	81.23

*

5. Fuel burning in the reactor BRUTs-25

To estimate the magnitude of the burn up of isotopes in the fuel of the BRUTs-25 reactor, we use the following ratio:

$$\Delta M\ (t) = \{1\text{-exp}\ (-F_n \bullet <\sigma_{fis}> \bullet t)\} \tag{1}$$

where $\Delta M\ (t)$ is the fraction of the burned out isotope mass, F_n is the neutron flux density in the core, 1 / (cm^2 • s); $<\sigma_{fis}>$ - one-group fission cross section, 10^{-24} cm^2; t is the isotope irradiation time in the core, s.

Table shows the estimates of the fraction of the burnt mass of $^{238\text{-}242}$Pu, ^{241}Am and ^{237}Np isotopes in the core centre, calculated according to relation (1) at $F_n = 2.6 \cdot 10^{15}$ 1 / cm^2 • s and t = 1000 eff. days = $8.64 \bullet 10^7$ s. It is assumed that for a period of one campaign equal to 1000 effective days, with a neutron fluence corresponding to this time, $F_n \bullet t = 2.25 \bullet 10^{23}$ 1 / cm^2, and a damaging dose of less than 75 dpa (displacements per atom), fuel rods with a cladding made of EP 823 steel will remain operational.

Table 3 Estimates of the mass of isotopes of fuel burned out during a campaign of 1000 effective days in the BRUTs-25

Fissile isotope and its percentage in the fuel at loading	Mass of fissile isotope at loading, M, kg	Mass of burned out isotope, M, kg	Fraction of burned out isotope, $\Delta M/M$, %
^{238}Pu, 0.567wt%	1.222	0.352	28.80
^{239}Pu, 30.026wt%	64.765	20.466	31.60
^{240}Pu, 10.239wt%	22.085	3.821	17.30
^{241}Pu, 1.938wt%	4.181	1.350	32.30
^{242}Pu, 1.962wt%	4.232	0.588	13.90
^{241}Am, 13.301wt%	28.689	4.303	15.00
^{237}Np, 0.348wt%	0.750	0.124	16.50

As for ^{241}Am, it is contained in BRUTs-25 fuel in an amount of 28.689 kg in the alloy, Pu-Am-Np-Zr. In accordance with the above burnout percentage of ^{241}Am, 15%, the mass of americium burned out in one campaign will be ΔM^{241}Am = 4.3 kg. Due to the close average cross sections for fission of ^{241}Am and radiation capture of neutrons, approximately the same amount of ^{241}Am is transmuted into ^{242}Am with subsequent rapid beta decay in ^{242}Pu (17.2%) and ^{242}Cm (82.8%). In this case, for the transmutation (conversion into fission products and radiation capture of neutrons) of ^{241}Am, produced by one VVER-1000 in 1 year, 25.75 kg [22], it will require work on the power of about 3 reactors of the BRUTs-25 type for 3 years.

The proposed scheme for burning actinides in an extremely rigid spectrum of low-power reactors can be considered, along with other scenarios currently proposed [22–25], to solve the problem of reducing the radiation hazard of long-lived highly active waste.

6. Conclusion

The concept of a lead reactor with a thermal capacity of 25 MW, powered by the innovative, now being developed, plutonium-americium-neptunium fuel, Pu-Am-Np-Zr, is proposed. The combination of this fuel, the small dimensions of the core and the lead coolant, ^{208}Pb, ensures extremely high average neutron energy of about 0.95 MeV in the center of the core and a high proportion of about 40 percent of neutrons with energies above 0.8 MeV. It was shown that in this extremely hard neutron spectrum, the values of one-group ^{241}Am and ^{237}Np fission cross sections are in the range of 0.7-0.8 barn, and the one-group cross sections of these weakly fissile isotopes differ from the one-group cross sections of well-fissile isotopes, $^{238,\ 239,\ 241}$Pu, no more than 2 times. This circumstance makes it possible to burn out the fissile isotopes of americium and neptunium by an amount of the order of 15–16% of the initial mass in one reactor campaign. The presence of ^{241}Am in charged innovative fuel, in the amount of 28.68 kg, allows us to transmute (translate into fission products and radiation capture of neutrons) about 8.6 kg of its mass over the time of about 3 years of operation of one reactor with a thermal power of 25 MW. For the transmutation of americium produced by one VVER-1000 in one year, 25.75 kg, it will require work on the power of about 3 reactors of the BRUTs-25 type for 3 years.

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