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Research Article

Reactor with metallic fuel and lead-208 coolant*

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Abstract

The paper considers the concept of a fast lead cooled 25MW reactor for a variety of applications, including incineration of minor actinides, production of medical radioisotopes, testing of radiation-damaged nuclear technology materials, etc. A specific feature of the proposed reactor is rather a high neutron flux of $2.6 \cdot 10^{15}$ n/(cm^2·s) at the core center, high average neutron energy of 0.95 MeV at the core center, and a large fraction (40%) of hard neutrons ($E_n > 0.8$ MeV). The extremely high estimated reactor parameters are achieved thanks to the small core dimensions (Dx$H \approx 0.50 \times 0.42$ m^2), innovative metallic fuel of the Pu-Am-Np-Zr alloy, and the ^{208}Pb enriched lead coolant. A relatively high probability of ^{241}Am fission (about 50%) is achieved in the reactor core's hard spectrum, this making it possible to incinerate up to 4 kg of ^{241}Am during one reactor campaign of 1000 effective days.

Keywords

Small reactor, plutonium-americium-neptunium fuel, lead-208 coolant, incineration of minor actinides

Introduction

At the present time, along with light sodium coolant, heavy lead-bismuth and lead coolants are considered for advanced fast reactors. The advantages of these include chemical inertness, minor activation, and small neutron absorption (Adamov et al. 1996, 1999). However, there is one more useful property of heavy coolants, the ability for low neutron moderation, which has not been given proper consideration. Low neutron moderation by lead is known to be caused by the fact that it has a large atomic mass (A = 207.2) and contains 52% of a stable lead isotope (^{208}Pb) with a high threshold value of inelastic neutron scattering (E_{thresh} = 2.63 MeV). The unique properties of ^{208}Pb as a promising coolant for fast reactor cores were addressed for the first time in (Shmelev et al. 1993). It was shown earlier in (Khorasanov and Blokhin 2013a, 2013b, 2014a, 2014b, 2015, 2017, Khorasanov 2013, 2015) that the average neutron energy could be increased by 6 to 7% in the inner subcore of the RBETs-M fast reactor with natural circulation (Alekseev et al. 2004) by substituting its standard lead-bismuth coolant for the ^{208}Pb enriched lead.

It is shown in the paper that the ^{208}Pb enriched lead coolant, in a combination with low moderating metal fuel, e.g. plutonium-americium-neptunium fuel (Vaganov et al. 2000, Harp et al. 2017), and small core dimensions ($D \times H$ ~ 0.50×0.42 m^2) can provide for an extremely high average energy of neutrons at the core center, which is close to 1 MeV, that is the amount that cannot be reached in the current fast medium sodium-cooled reactors (BN-600 and BN-800) (Khorasanov and Blokhin 2012).

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A reactor with extremely hard neutrons can be used in a variety of applications, primarily, for incineration of environmentally hazardous minor actinides (^{237}Np, ^{241}Am, and ^{244}Cm) with a high threshold value of nuclei fission (E_{thresh} > 0.8 MeV), as well as to study the radiation damage to nuclear technology materials caused largely through the action of fast neutrons. The paper considers the possibility for obtaining a hard spectrum of neutrons in a small reactor of 25 MW(th) but with parameters sufficient for the noticeable (~ 15%) incineration of low fissionable nuclides during one reactor campaign. It is also suggested that the reactor campaign is limited only by the neutron fluence growth to the value which does not lead to a catastrophic damage to the fuel cladding.

BRUTs-25 reactor concept

The design of the BRUTs fast training reactor was discussed in (Samokhin et al. 2015). Its optimization and conversion to the incineration mode consisted in increasing its thermal power and using innovative zirconium-alloyed metallic fuel (Harp et al. 2017, Khorasanov et al. 2017, 2018, Khorasanov and Samokhin 2017). The design parameters of the BRUTs-25 reactor are presented in Table 1.

Calculation method

The core center neutron fluxes for the BRUTs-25 reactor were calculated using the MCNP/4B code (Briesmeister 1997) at IPPE. Based on these and using the nuclear constants prepared (Blokhin et al. 2011) from the ENDF/B-VII.0 library, the following neutronic parameters have been calculated: the average neutron energy at the core center; the fraction of hard neutrons, E_n > 0.8 MeV, at the core center; the one group cross sections of the $^{238–242}$Pu, ^{241}Am and ^{237}Np fission and nuclei neutron radiation capture, and the probabilities of these nuclei fission.

Fig. 1 presents the calculated spectra of neutrons at the center of the BRUTs-25 reactor core with different coolants (^{nat}Pb и ^{208}Pb).

Calculation results

Table 2 presents the calculation results for neutronic parameters of the BRUTs-25 reactor and several transuranics.

The table uses the following calculation pattern:

– the probability of the P_{fis} nuclei fission was calculated based on the relation $P_{fis} = [\sigma_{fis}] / ([\sigma_{fis}] + [\sigma_{cap}])$, where $[\sigma_{fis}]$ and $[\sigma_{cap}]$ are one-group cross-sections of nucleus fission and cross-sections of the neutron radiation capture by nucleus respectively;
– composition of the power-grade plutonium after 20 years of decay in wt. %: ^{237}Np – 0.10, ^{238}Pu – 1.19, ^{239}Pu – 63.05, ^{240}Pu – 21.50, ^{241}Pu – 4.07, ^{242}Pu – 4.12, ^{241}Am – 5.87.

Table 1. Design parameters of the BRUTs-25 reactor.

Parameter	Value
Thermal power, MW	25
Equivalent core diameter, mm	500
Core height, mm	418
Number of FAs in core	7
Number of pins in FA	165
Core heat density, kW/l	293
Average linear thermal load on pin, kW/m	50
FA flat-to-flat dimension, cm	20.1
FA pitch, cm	20.2
Pin inner diameter, mm	8.2
Cladding thickness, mm	0.3
Fuel pellet diameter, mm	7.4
Pin pitch, mm	14
Fuel, wt. %	Pu_{en}47.6+Am10.5+Np0.3+Zr41.6
Fuel density, g/cm^3	10.3
Coolant	^{208}Pb
Core inlet/outlet coolant temperature, °C	450 / 530
Cladding surface temperature, °C	610
In-core volume fraction of coolant/fuel/structural material, %	69 / 25 / 6
Core loaded fuel weight, kg	215.8
Core loaded weight of power-grade Pu, kg	102.72
In-core Am-241 weight, kg	28.68
In-core Np-237 weight, kg	0.75
k_{eff} with fuel loaded into reactor	1.01616 ± 0.00029
Core center neutron flux, 1/(cm^2·s)	2.6·10^{15}
Campaign, eff. days	1000

Table 2. Neutronic parameters of the BRUTs-25 reactor core and several transuranics. OCNRCN – One-group cross-section for neutron radiation capture by nucleus.

Parameter	Value
Core center average neutron energy [E_n], MeV	0.955
Fraction of fast neutrons E_n > 0.1 MeV, %	89.34
Fraction of hard neutrons E_n > 0.8 MeV, %	40.28
One-group cross-section for ^{238}Pu fission, barn	1.516
OCNRCN for ^{238}Pu, barn	0.298
Probability of ^{238}Pu fission, %	83.56
One-group cross-section for ^{239}Pu fission, barn	1.684
OCNRCN for ^{239}Pu, barn	0.128
Probability of ^{239}Pu fission, %	92.95
One-group cross-section for ^{240}Pu fission, barn	0.836
OCNRCN for ^{240}Pu, barn	0.178
Probability of ^{240}Pu fission, %	82.45
One-group cross-section for ^{241}Pu fission, barn	1.754
OCNRCN for ^{241}Pu, barn	0.174
Probability of ^{241}Pu fission, %	90.98
One-group cross-section for ^{242}Pu fission, barn	0.670
OCNRCN for ^{242}Pu, barn	0.155
Probability of ^{242}Pu fission, %	81.23
One-group cross-section for ^{241}Am fission, barn	0.731
OCNRCN for ^{241}Am, barn	0.708
Probability of ^{241}Am fission, %	50.81
One-group cross-section for ^{237}Np fission, barn	0.821
OCNRCN for ^{237}Np, barn	0.540
Probability of ^{237}Np fission, %	60.30

It follows from the presented data that the values of the one-group nuclear fission cross-sections for $^{240, 242}$Pu, ^{241}Am, and ^{237}Np in the hard neutron spectrum at the

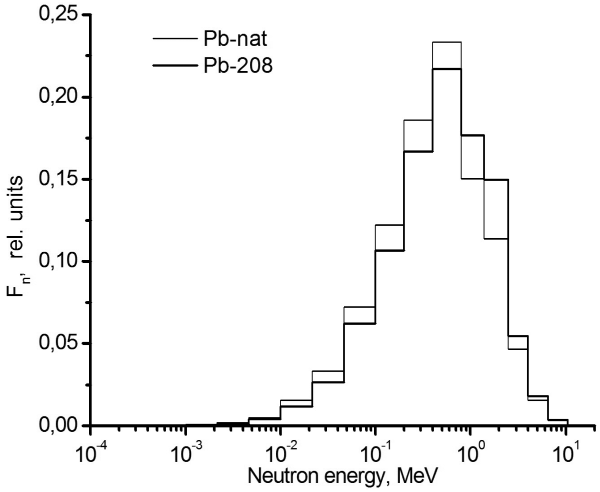

Figure 1. Spectra of neutrons at the core center for the nat Pb and 208Pb cooled BRUTs-25 reactor. The fractions of hard neutrons of En > 0.8 MeV are respectively 32.97 and 40.28%.

BRUTs-25 reactor core center differ by not more than twice from the values of the one-group cross-sections for the highly fissionable plutonium isotopes ($^{238, 239, 241}Pu$).

Incineration of actinides in the BRUTs-25 reactor fuel

We shall use the following relation to estimate the value of the isotope incineration in the BRUTs-25 reactor fuel:

$$\Delta M(t) = \{1 - \exp(-\Phi_n \cdot [\sigma_{fis}] \cdot t)\}, \quad (1)$$

where $\Delta M(t)$ is the fraction of the incinerated isotope mass; Φ_n is the neutron flux at the core center, $1/(cm^2 \cdot s)$; $[\sigma_{fis}]$·is the one-group cross-section of the isotope nucleus fission, 10^{-24} cm^2; and t is the isotope irradiation time, s.

Table 3 presents the estimated fractions of the incinerated $^{238-242}Pu$ and ^{241}Am isotope mass for the BRUTs-25 reactor core calculated based on relation (1) with Φ_n = $2.6 \cdot 10^{15}$ $1/(cm^2 \cdot s)$ and t = 1000 eff. days = $8.64 \cdot 10^7$ s. It is assumed that pins with the cladding of EP 823 steel will remain serviceable during one reactor campaign, equal to 1000 eff. days, with the neutron fluence consistent with this time ($\Phi_n \cdot t = 2.25 \cdot 10^{23}$ $1/cm^2$) and the damaging dose less than 75 dpa (displacements per atom).

The results of the actinide incineration in fuel during one BRUTs-25 reactor life can be summed up as follows:

- out of 125.92 kg of loaded fissionable isotopes, 31.00 kg or 24.62 wt. % are incinerated;
- the most highly incinerated isotopes are fissionable isotopes of plutonium ($^{238, 239, 241}Pu$) in the amount of 28 to 32 wt. % of the initial mass of fissionable isotopes;
- ^{241}Am and ^{237}Np are incinerated in the amount of 15 to 16 wt. % of their initial mass;
- the percent content of the $^{238-242}Pu$, ^{241}Am and ^{237}Np isotopes in non-incinerated Pu changes insignificantly or by 1 to 5 %, as compared with their initial percent content in $Pu_{power-grade}$.

As to ^{241}Am, this is contained in the BRUTs-25 fuel in the amount of 28.68 kg, including 6.03 kg contained in power-grade plutonium and 22.65 kg contained in the Pu_{energ}-Am-Np-Zr alloy. In accordance with the above ^{241}Am incineration percentage (15%), the mass of the americium incinerated during one reactor campaign will be ΔM_{Am241} = 4.3 kg. And another 4.3 kg of ^{241}Am are transmuted into ^{242}Am decaying further rapidly to ^{242}Cm and ^{242}Pu.

In this case, transmutation (conversion to fission products) of the americium generated by one VVER-1000 reactor during one year (25.75 kg (Gulevich et al. 2013)) will require power operation of six small BRUTs-25 reactors for about three years.

The proposed actinide incineration pattern in an extremely hard spectrum of small reactors can be considered along with other currently suggested scenarios (Gulevich et al. 2013, Haas Didier et al. 2015, Kazansky and Romanov 2014, Kazansky et al. 2016) to solve the problem of reducing the radiation hazard from long-lived high-level waste.

Table 3. Estimated fuel isotope mass incinerated during a life of 1000 eff. days in the BRUTs-25 reactor core.

Fissionable isotope and its percent content in loaded fuel	Mass of fissionable isotope with the load M, kg	Mass of incinerated isotope, ΔM, kg	Fraction of incinerated isotope, ΔM/M, %	Mass of non-incinerated isotope and its percent content in fuel at the end of campaign
^{238}Pu, 0.57 wt. %	1.22	0.35	28.78	0.87 kg, 0.47 wt. %
^{239}Pu, 30.01 wt. %	64.77	20.47	31.60	44.30 kg, 23.99 wt. %
^{240}Pu, 10.23 wt. %	22.09	3.82	17.30	18.26 kg, 9.89 wt. %
^{241}Pu, 1,94 wt. %	4.18	1.35	32.30	2.83 kg, 1.53 wt. %
^{242}Pu, 1,96 wt. %	4.23	0.59	13.90	3.644 kg, 1.97 wt. %
^{241}Am, 13,29 wt. %	28.68	4.30	15.00	24.38 kg, 13.20 wt. %
^{237}Np, 0,40 wt. %	0.75	0.12	16.50	0.66 kg, 0.34 wt. %
Total: 58.40 wt. % in fuel of 215.8 kg	Total: 125.92 kg	Total: 31.00 kg		Total: 94.91 kg, 51.39 wt. % in fuel of 184.69 kg

Conclusion

A concept has been proposed of a lead-cooled 25MW(th) reactor with innovative plutonium-americium-neptunium fuel (Pu-Am-Np-Zr) currently under development. This fuel, combined with the small core dimensions and ^{208}Pb lead enriched coolant, provides for an extremely high average energy of neutrons (about 0.95 MeV at the core center) and a high fraction (~ 40%) of neutrons with the energy of over 0.8 MeV to be achieved. It has been shown that, in this extremely hard spectrum of neutrons, the values of the one-group cross-sections of the ^{241}Am and ^{237}Np isotope fission are in a range of 0.7 to 0.8 barn with the one-group cross-sections of these low fissionable isotopes differing from the one-group cross-sections of highly fissionable isotopes of $^{238, 239, 241}$Pu by not more than twice. This circumstance makes it possible to incinerate low fissionable isotopes of americium and neptunium by about 15 to 16 % of the initial mass during one reactor campaign. The presence of 28.68 kg of ^{241}Am in the loaded innovative fuel allows 4.3 kg of its mass to be transmuted (converted to fission products) during three years of one 25 MW(th) reactor operation. Incineration of the americium generated by one VVER-1000 reactor during one year (25.75 kg) will require power operation of six BRUTs-25 reactors for about three years.

The proposed method for the conversion of ^{241}Am and ^{237}Np to fission products can be considered along with other currently proposed scenarios of actinide transmutation for reducing the long-lived RW hazard.

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