NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 4(2): 99–102
DOI 10.3897/nucet.4.30527

Research Article

Lead reactor of small power with metallic fuel*

Georgiy L. Khorasanov[1], Dmitriy S. Samokhin[1], Aleksandr S. Zevyakin[1], Yevgeniy A. Zemskov[2], Anatoliy I. Blokhin[3]

1 *Obninsk Institute for Nuclear Power Engineering, NRNU MEPhI, 1 Studgorodok, Obninsk, Kaluga Reg., 249040, Russian Federation*

2 *SSC IPPE, 1 Bondarenko Sq., Obninsk, Kaluga Reg., 249033, Russian Federation*

3 *Nuclear Safety Institute of the Russian Academy of Sciences, 52 Bolshaya Tulskaya St., Moscow, 115191, Russian Federation*

Corresponding author: *Georgiy L. Khorasanov* (khorasanow@yandex.ru)

Academic editor: *Yury Korovin* ♦ **Received** 13 October 2018 ♦ **Accepted** 8 November 2018 ♦ **Published** 26 November 2018

Citation: Khorasanov GL, Samokhin DS, Zevyakin AS, Zemskov YA, Blokhin AI (2018) Lead reactor of small power with metallic fuel. Nuclear Energy and Technology 4(2): 99–102. https://doi.org/10.3897/nucet.4.30527

Abstract

The possibility for obtaining a hard neutron spectrum in small reactor cores has been considered. A harder spectrum than spectra in known fast sodium cooled and molten salt reactors has been obtained thanks to the selection of relatively small core dimensions and the use of metallic fuel and natural lead (^{nat}Pb) coolant. The calculations for these compositions achieve an increased average neutron energy and a large fraction of hard neutrons in the spectrum (with energies greater than 0.8 MeV) caused by a minor inelastic interaction of neutrons with the fuel with no light chemical elements and with the coolant containing 52.3% of ^{208}Pb, a low neutron-moderating isotope.

An interest in creating reactors with a hard neutron spectrum is explained by the fact that such reactors can be practically used as special burners of minor actinides (MA), and as isotope production and research reactors with new consumer properties. With uranium oxide fuel (UO_2) substituted by metallic uranium-plutonium fuel (U-Pu-Zr), the reactors under consideration have the average energy of neutrons and the fraction of hard neutrons increasing from 0.554 to 0.724 MeV and from 18 to 28% respectively. At the same time, the one-group fission cross-section of ^{241}Am increases from 0.359 to 0.536 barn, while the probability of the ^{241}Am fission increases from 22 to 39%. It is proposed that power-grade plutonium resulting from regeneration of irradiated fuel from fast sodium cooled power reactors be used as part of the fuel for future burner reactors. It contains unburnt plutonium isotopes and some 1% of MAs which transmutate into fission products in the process of being reburnt in a harder spectrum. This will make it possible to reduce the MA content in the burner reactor spent fuel and to facilitate so the long-term storage conditions for high-level nuclear waste in dedicated devices.

Keywords

Fast reactor; hard neutron spectrum; metallic uranium-plutonium fuel; natural lead coolant; americium-241

Introduction

Currently, the issues of the MA transmutation into the fission products of these nuclei receive a great deal of attention in literature. The content of ^{241}Am, e.g. in the MOX fuel of thermal reactors, needs to be minimized both for the safe handling of fuel in the process of its fabrication and for safe reactor control. The presence of large amounts of ^{241}Am in disposable high-level waste (HLW) is also undesirable due to large quantities of heat it releases and its high volatility.

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2018, n.1, pp. 99–111.

In one of the scenarios of a two-component (VVER+BN) nuclear power system (Troyanov 2016) in Russia, as it is known, fast sodium cooled reactors (BN) are expected to have the role as producers of plutonium for the MOX fuel of thermal reactors. And BN reactors will be fueled with power-grade plutonium obtained by regeneration of irradiated fuel from VVER reactors. Low-fission MAs in spent nuclear fuel (SNF) are expected to be converted into fission products. However, the neutron spectrum in fast sodium and lead cooled reactor cores appears to be not hard enough for the effective MA transmutation as the average core neutron energy does not exceed 0.5 MeV (Khorasanov and Blokhin 2013), this limiting the probability of the ^{241}Am fission to about 15%. As a result, some of the MAs remain unburnt or are converted into long-lived isotopes, and the equilibrium content of MAs in fast reactors may reach around 1 % (Lopatkin 2013). These MAs withdrawn from the SNF of BN reactors shall be either disposed or reburnt in a hard spectrum burner reactor in which the MA fission probability exceeds 15%.

This paper considers the feasibility of creating such reactor with a harder neutron spectrum using innovative fuel compositions and innovative heavy liquid metal coolant.

The purpose of the study is to show numerically the possibility of achieving a high probability of the ^{241}Am fission (over 15 %) in innovative hard neutron spectrum reactors.

BRUTs reactor (Samokhin et al. 2015) with uranium oxide fuel and BRUTs-M2 reactor (Khorasanov and Samokhin 2017) with metallic uranium-plutonium fuel (Vaganov et al. 2000, Aitkalieva 2016) have been considered as innovative reactors. The fuel composition calculations at this stage used the isotopic composition of power-grade plutonium produced from SNF of light water thermal reactors. Additional calculations will be needed to obtain data on the isotopic vector of the plutonium withdrawn from BN reactors with MOX fuel.

BRUTs and BRUTs-M2 reactors

The BRUTs reactor was proposed by the Obninsk Institute for Nuclear Power Engineering, NRNU MEPhI, as a training reactor. It was upgraded for operation as a burner reactor (BRUTs-M2) with the reactor power increased and the uranium oxide fuel substituted for zirconium doped uranium-plutonium fuel. The parameters of the BRUTs and BRUTs-M2 reactors are presented in Table 1.

Calculation procedure

The neutron fluxes in the BRUTs and BRUTs-M2 core centers were calculated at the Institute of Physics and Power Engineering (IPPE) with a 28-group neutron spectrum approximation by Monte Carlo method using the MCNP/4B code (Briesmeister 1997) with a library of cross-sections based on the ENDF/B-VII.1 evaluated nuclear data files. The following neutronic parameters were calculated based on the obtained neutron spectra and using the same nuclear constants: one-group neutron energy in the core center (energy averaged upon the core center neutron spectrum); fraction of hard (E_n > 0.8 MeV) neutrons in the core center neutron spectrum; one-group fission cross-sections for the $^{235, 238}$U, $^{238, 239, 240, 241, 242}$Pu, and ^{241}Am isotopes; cross-sections of the radiative neutron capture by these nuclei; probabilities

Table 1. BRUTs and BRUTs-M2 reactor parameters.

Parameter	BRUTs value	BRUTs-M2 value
Thermal power, MW	0.5	15
Equivalent core diameter, mm	618	460
Core height, mm	620	500
Number of FAs in core	7	7
Number of pins in FA	252	125
FA flat-to-flat dimension, cm	17	17
FA spacing, cm	17.2	17.2
Outer diameter of pin, mm	12.7	9
Fuel cladding thickness, mm	0.5	0.4
Fuel pellet diameter, mm	11.5	8.0
Fuel spacing, mm	14	14
Fuel	UO_2	U 53 (^{235}U-19.7%) + Pu 30 + Zr 17
Fuel density, g/cm^3	10.5	13.37
Coolant	^{nat}Pb	^{nat}Pb
Core inlet/outlet coolant temperature, °C	460 / 500	450 / 500
Fuel cladding surface temperature, °C	550	550
In-core coolant/fuel/structural material volume fraction, %	26 / 67 /7	63 / 30 / 7
Core fuel load weight, kg	1176	293
Loaded weight of fissile nuclides	205 kg ^{235}U	88 kg Pu and 31 kg ^{235}U
Reactor fueling K_{eff}	1.00721±0.00082	1.00018±0.00086
Core center neutron flux, 1/cm^2·s	1.6·10^{13}	1.4·10^{15}

of fission for these nuclei. The probability of the ^{241}Am fission, $P_{f\,Am241}$, was calculated from the relation $P_{f\,Am241} = \langle\sigma_{fisAm241}\rangle / (\langle\sigma_{fisAm241}\rangle + \langle\sigma_{capAm241}\rangle)$, where $\langle\sigma_{fisAm241}\rangle$ and $\langle\sigma_{capAm241}\rangle$ are one-group cross-sections of the ^{241}Am nucleus fission and cross-sections of the radiative neutron capture by the ^{241}Am nucleus respectively. The same procedure was used to calculate the probabilities of the U and Pu isotope nuclei fission.

Calculation results

Table 2 presents the results of calculating the neutron characteristics of the BRUTs and BRUTs-M2 reactor cores and one-group nuclear cross-sections of actinides in the calculated neutron spectra of the reactor cores.

It follows from Table 2 that the use of the U-Pu-Zr metallic fuel instead of uranium oxide fuel and of heavy ^{nat}Pb coolant in a small core reactor leads to an increase in:

– the average energy of neutrons in the core center (by 30%);
– the fraction of hard neutrons, E_n > 0.8 MeV, in the core center neutron spectrum (by 57%);
– the one-group cross-section of the ^{238}U nucleus fission (by 35%) and the probability of its fission (by 65%);
– the one-group cross-sections of the $^{240,\,242}$Pu nuclei fission (by 40 to 50%) and the probabilities of their fission (by 30 to 37%);
– the one-group cross-section of the ^{241}Am nuclei fission (by 49%) and the probability of its fission (by 78%).

Conclusion

It has been shown that rather a hard spectrum of neutrons with the average neutron energy of $\langle E_n\rangle$ = 0.724 MeV in the core center and a large fraction (28%) of neutrons with an energy greater than 0.8 MeV is achieved in a lead fast reactor with a small sized core of $D \times H = 0.46 \times 0.5$ m^2 and metallic fuel (U53wt%+Pu30wt%+Zr17wt%).

The calculated probability of the ^{241}Am fission in the hard neutron spectrum of the BRUTs-M2 fast lead cooled reactor has a value of around 39%, which is 2 to 2.5 times as high as the probability value of this isotope fission in sodium fast reactors. At the same time, the one-group cross-section of the ^{241}Am nuclei fission is 0.536 barn, which is also 2 to 2.5 times as high as the cross-section value of this isotope in sodium fast reactors.

The proposed method to increase the MA nuclei fissionability in the cores of lead reactors with metallic fuel can be used to reburn equilibrium MA residues in SNF

Table 2. Neutronic parameters of the BRUTs and BRUTs-M2 reactor cores and the actinide isotope range.

Parameter	BRUTs value	BRUTs-M2 value	Variation of BRUTs-M2 value against BRUTs value, %
Core center average neutron energy, $\langle E_n\rangle$, MeV	0.554	0.724	+ 30.69
Hard neutron fraction, E_n > 0.8 MeV, %	18.11	28.45	+ 57.10
One-group ^{235}U fission cross-section, barn	1.550	1.338	–13.68
OCNRC *) for ^{235}U, barn	0.362	0.238	–34.25
Probability of ^{235}U fission, $P_{f\,U235}$, %	81.07	84.90	+ 4.72
One-group ^{238}U fission cross-section, barn	0.059	0.080	+35.59
OCNRC for ^{238}U, barn	0.210	0.140	–33.33
Probability of ^{238}U fission, $P_{f\,U238}$, %	21.93	36.36	+65.80
One-group ^{238}Pu fission cross-section, barn	1.166	1.369	+17.41
OCNRC for ^{238}Pu, barn	0.499	0.341	–31.66
Probability of ^{238}Pu fission, $P_{f\,Pu238}$, %	70.03	80.06	+14.32
One-group ^{239}Pu fission cross-section, barn	1.649	1.647	–0.12
OCNRC for ^{239}Pu, barn	0.275	0.154	–44.00
Probability of ^{239}Pu fission, $P_{f\,Pu239}$, %	85.71	91.46	+ 6.71
One-group ^{240}Pu fission cross-section, barn	0.471	0.667	+ 41.61
OCNRC for ^{240}Pu, barn	0.335	0.206	–38.51
Probability of ^{240}Pu fission, $P_{f\,Pu240}$, %	58.44	76.40	+30.73
One-group ^{241}Pu fission cross-section, barn	2.062	1.795	–12.95
OCNRC for ^{241}Pu, barn	0.294	0.196	–33.33
Probability of ^{241}Pu fission, $P_{f\,Pu241}$, %	87.52	90.16	+ 3.02
One-group ^{242}Pu fission cross-section, barn	0.344	0.517	+ 50.29
OCNRC for ^{242}Pu, barn	0.289	0.178	–38.41
Probability of ^{242}Pu fission, $P_{f\,Pu242}$, %	54.34	74.43	+ 36.97
One-group fission cross-section, ^{241}Am, barn	0.359	0.536	+ 49.30
OCNRC for ^{241}Am, barn	1.281	0.835	–34.82
Probability of ^{241}Am fission, $P_{f\,Am241}$, %	21.89	39.10	+ 78.62

* OCNRC – one-group cross-section of nuclear radiative capture

of sodium fast reactors as part of the two-component (VVER+BN) nuclear power system in Russia.

Apart from its key function as a burner reactor, the hard neutron spectrum reactor can be used for production of medical isotopes through the (n, p) and (n, α) reactions, which are not readily achievable in currently effective isotope production reactors.

References

- Aitkalieva A, Papesch CA (2017) Microstructural characterization of metallic transmutation fuels. Presentation at the 14-th Information Exchange Meeting on Actinide and Fission Products Partitioning and Transmutation, IEMPT-14, 17-20 October 2016, San Diego, USA. Abstract is published in the IEMPT-14 Proceedings: NEA/NSC/R 3, 181–182.
- Briesmeister JF (1997) MCNP – A General Monte Carlo N-Particle Transport Code, Version 4B, LA-12625-M, Los Alamos National Laboratory.
- Khorasanov GL, Blokhin AI (2012) Selected macroscopic characteristics of medium sized fast reactors. Izvestiya vuzov. Yadernaya energetika 2012(3):18–22. [in Russian]
- Khorasanov GL, Samokhin DS (2017) A concept of small BRUTs-series reactors. Proc. of the 2nd Int. Conf. of Young Scientists, Specialists, Postgraduates and Students, "Innovative Small and Very Small Nuclear Reactors", 15–17 May, Obninsk. INPE NRNU MEPhI Publ., 19–21. [in Russian]
- Lopatkin AV (2013) Fuel cycle of large-scale nuclear power in Russia based on principles of fuel and radiation balance and non-proliferation. Dr. Tech. Sci. Diss. SSC RF-IPPE Publ., Obninsk, 45 pp. [in Russian]
- Samokhin DS, Khorasanov GL, Tormyshev IV, Zemskov YeA, Gostev AL, Terekhova AM, Kuzmichev SA (2015) A small fast lead cooled reactor for training purposes. Izvestiya vuzov, Yadernaya energetika 2015(3): 135–141. [in Russian]
- Troyanov VM (2016) Two plus one. A system of two components (VVER and BN) as the basis for the future and for solving the SNF problem. Journal of Rosenergoatom 2016(9): 22–29. [in Russian]
- Vaganov IV, Gadzhiyev GI, Kosulin NS, Syuzev VN (2000) Results of the tests and postirradiation examination of the UPTs-1 FA with metallic U-Pu-Zr fuel. Proc. of the 6th International Conference on Reactor Materials. Dimitrovgrad. NIIAR Publ., 2. [in Russian]