KnE Engineering

AtomFuture-2017
XIII International Youth Scientific and Practical Conference
"FUTURE OF ATOMIC ENERGY - AtomFuture 2017"
Volume 2017

Conference Paper

The Impact of Isotopic Composition of Lead on the Neutron-Physical Characteristics of Fast Reactor with Liquid Metal Coolant

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Received: 23 December 2017
Accepted: 15 January 2018
Published: 21 February 2018

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the AtomFuture Conference Committee.

Abstract

It is well known, that lead coolant, highly enriched by ^{208}Pb, has some advantages over other coolants. It is predicted that the use of ^{208}Pb in the reactor core will lead to an increase in the production of plutonium and transmutation of long-lived decay products. The main objective of this paper was to investigate the influence of the isotopic composition on the fast reactor neutron-physical characteristics. For this purpose we used the RBETS-M benchmark - a fast energy reactor that includes 12 zones with different sizes and temperatures of the materials. Calculations were performed for homogeneous and heterogeneous models. Our calculations show that the replacement of the coolant with the natural lead to ^{208}Pb and ^{208}Pb together with Bi can substantially improve the neutron-physical characteristics of the fast reactor, in particular by reducing the initial reactivity margin. Studies of the heterogeneity effect in the reactor model showed an increase in the effective multiplication factor of about 1.5% at the end of the campaign.

1. Introduction

At present, active research is being carried out in the field of application of various heavy liquid metal coolants for different types of fast reactors, such as, for example, BREST-OD-300 with lead coolant and SVBR-100 with lead-bismuth coolant, which are already in the stage completion of technical design (see, for example, [1-4]). Natural lead contains a number of isotopes, the neutron-physical properties of which differ significantly from each other. Therefore, the main purpose of the proposed work was to study the effect of the isotope composition of lead in the coolant on the neutron-physical characteristics of a test fast reactor (see, for example, [5-6]). In [5-6] it was

How to cite this article: M. M. Ivanova, V. V. Kolesov, V. V. Korobeinikov, A. M. Terehova, and G. L. Khorasanov, (2017), "The Impact of Isotopic Composition of Lead on the Neutron-Physical Characteristics of Fast Reactor with Liquid Metal Coolant" in *XIII International Youth Scientific and Practical Conference "FUTURE OF ATOMIC ENERGY - AtomFuture 2017"*, KnE Engineering, pages 400–410. DOI 10.18502/keg.v3i3.1640

shown that lead, strongly enriched with ^{208}Pb, has undeniable advantages over other heat carriers. This material has a very low neutron capture cross section and is a weak neutron moderator in elastic scattering throughout the reactor energy range because of its large atomic weight and in inelastic scattering of fast neutrons because of the high energy threshold of the nuclide excitation reaction. However, certain problems remain with the accuracy of estimates of the inelastic scattering cross section (see, for example, Refs [7-8]. ^{208}Pb is safer than light coolants. It is predicted that the use of ^{208}Pb in reactors will lead to an increase in the production of plutonium and to the transmutation of long-lived decay products Compared with the lead-bismuth eutectic, ^{208}Pb has a much lower post-operational toxicity and does not require the consumption of bismuth, which, with increasing consumption, can become a very scarce metal. A project of a lead-bismuth reactor RBEC-M with a capacity of 900 MW (thermal) was proposed in [9] as a benchmark for calculating the fuel cycle. The project was developed in the 2000s at the Kurchatov Institute. The reactor coolant is a lead-bismuth eutectic (56% Bi- 44% Pb). The share of lead isotopes in the coolant: 208Pb - 52.8%, 207Pb - 22.6%, 206Pb - 24.6%. As fuel, mixed uranium-plutonium nitride is used. In this case, plutonium obtained after processing spent fuel of light water reactors is used. The core is surrounded on all sides by a reproduction zone, where depleted uranium nitride is used. Even further along the radius of the reactor is a neutron reflector. The campaign lasts 1800 effective days.

The proposed benchmark was used to study the effect of lead isotope composition on the neutron-physical characteristics of a fast reactor.

2. The reactor core model

The core model includes 12 physical zones, differing from each other in the size and temperature of the materials (Figures 1, 2). The main dimensions of physical zones and their temperatures are given in Table. 1. The fuel cells of the heterogeneous model of the core, its dimensions and composition are shown in Fig. 3 and in Table. 2, 3.

To study the effect of the isotope composition of lead on the neutron-physical characteristics of a fast reactor, several models of the coolant for the RBEC-M reactor were created:Model 1 (homogeneous and heterogeneous) – the coolant consists of natural lead (52.4% of ^{208}Pb / 22.1% of ^{207}Pb / 24.6% of ^{206}Pb) and bismuth - (56% of Bi and 44% of Pb); Model 2 (heterogeneous) - the coolant consists of ^{208}Pb and bismuth - (56% of Bi and 44% of ^{208}Pb); Model 3 (heterogeneous) - the coolant consists of ^{208}Pb;

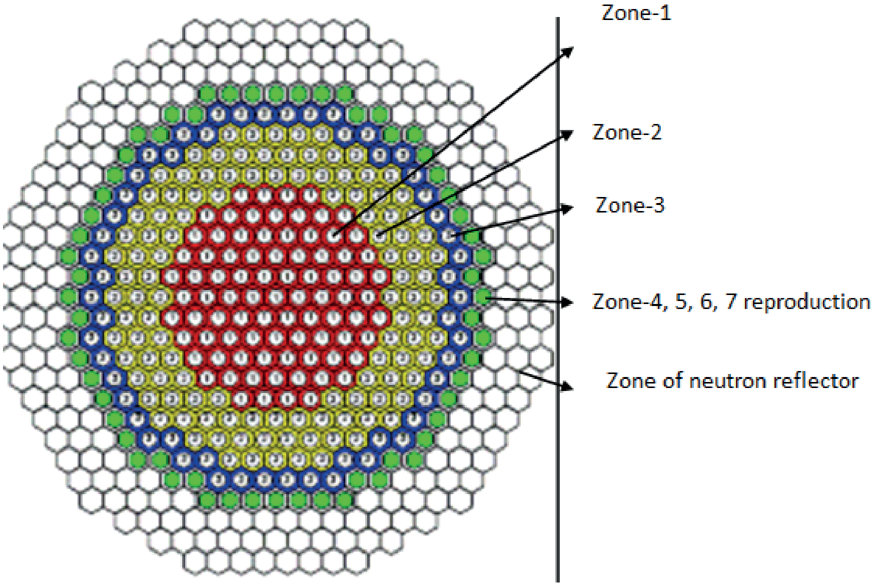

Figure 1: The cross-section of the core of the RBEC-M reactor (the numbering of the zones - see Table 1).

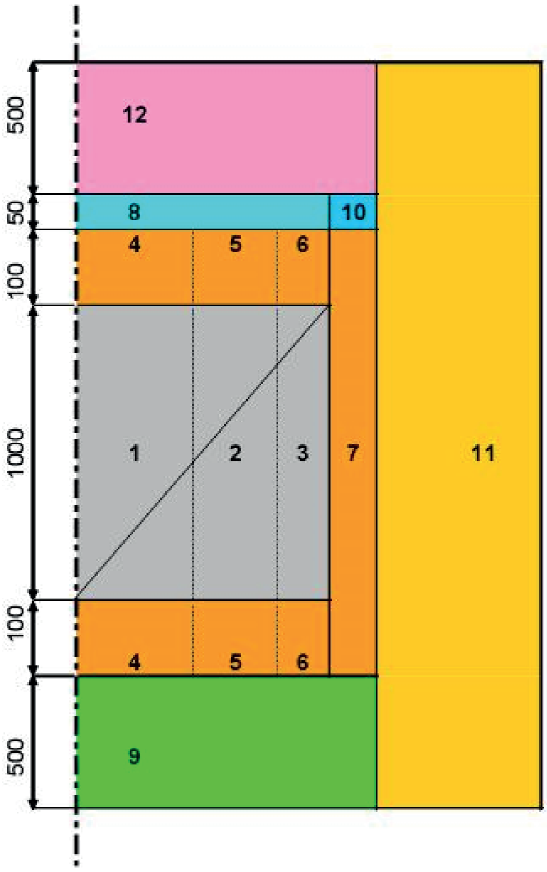

Figure 2: The location of the zones in the RBEC-M reactor (longitudinal section, dimensions given in mm, numbering of the zones - see Table 1).

Table 1: Dimensions and temperatures of the physical zones of the core of the RBEC-M reactor.

Физические зоны	Zone	Inner radius, cm	External radius, cm	Height, cm	Fuel temperature, K	Temperature of steel, K	Coolant temperature, K
Low enrichment zone	1	-	86.16	100	1200	800	700
Middle Enrichment Zone	2	86.16	131.84	100	1100	800	700
Zone of high enrichment	3	131.84	148.65	100	1000	800	700
Reproduction zone-1	4	-	86.16	10	900/700*	800/600*	800/600*
Reproduction zone-2	5	86.16	131.84	10	900/700*	800/600*	800/600*
Reproduction zone-3	6	131.84	148.65	10	900/700*	800/600*	800/600*
Reproduction zone-4	7	148.65	165.34	120	700	600	600
Upstream end core assemblies	8	-	148.65	5	-	800	800
The collection of gases of fuel elements	9	-	165.34	50	-	600	600
Up the fuel assemblies of the reproduction zone	10	148.65	165.34	5	-	600	600
Side reflector	11	165.34	211.26	225	-	700	700
Up the reactor	12	-	165.34	50	-	800	800

* - at the top / bottom of physical zones

Table 2: Dimensions of the fuel cell of the heterogeneous model, mm.

	Zone 1, 4	Zone 2, 5	Zone 3, 6	Zone 7
Diameter of fuel pellet	5.7	6.2	7.2	9.7
Radial width of the gas gap	0.15	0.15	0.15	0.1
Shell thickness	0.5	0.5	0.5	0.5
Outer shell diameter	7.0	7.5	8.6	11.0

Model 4 (heterogeneous) - the coolant consists of ^{206}Pb. Model 5 (heterogeneous) - the coolant consists of natural lead (52.4% of ^{208}Pb / 22.1% of ^{207}Pb / 24.6% of ^{206}Pb).

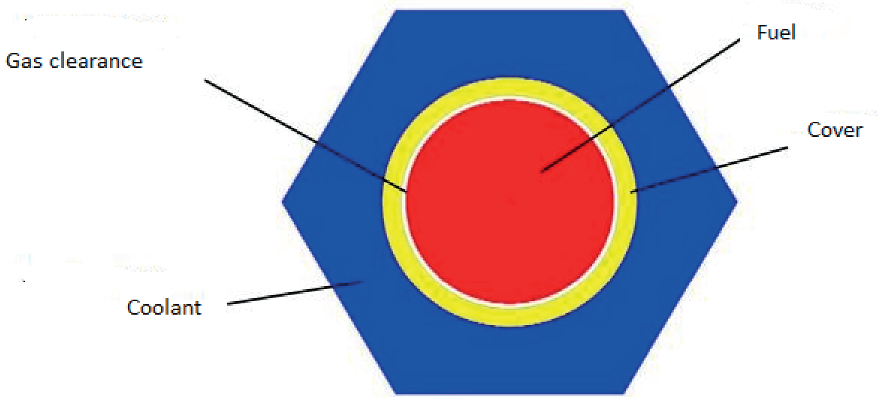

Figure 3: The RBEC-M reactor cell in the heterogeneous core model.

Table 3: Fuel composition in the heterogeneous reactor model RBEC-M.

CORE	Reproduction zone
(U 0.863+Pu 0.137) N Uranium mining enrichment 0,1 %. Composition of plutonium: ^{238}Pu/^{239}Pu/ ^{240}Pu $^{/241 Pu}$/^{242}Pu 1,3% / 61% / 24,4% / 8,3% / 5%.	Uranium mining enrichment 0,1 %.

Different lead isotopes have a number of important features. Thus, the ^{208}Pb has a low neutron absorption cross section and a weak neutron slowing down. The disadvantage is that it is the main source of polonium. It gives increasing of activity. There is also another lead isotope - ^{206}Pb, which is slightly activated, and it generates less polonium during the campaign.In the RBEC-M reactor, the average neutron energy is approximately 0.42 MeV, averaged over the three zones of the reactor. When the coolant, using natural lead, changes to the coolant enriched in ^{208}Pb, the average neutron energy becomes approximately equal to 0.44 MeV [10-11].

Fig. 4 shows the dependence of the microscopic radiative capture cross sections for different lead isotopes in the twenty-eight group in the BNAB group system. It is seen from the figure that in the neutron energy range En = 0.1-20.0 MeV, the microscopic neutron radiative capture cross section by the ^{208}Pb isotope is 1.5 to 2 times lower than the corresponding cross section for natural lead, and at intermediate neutron energies, En < 50 keV, the difference in the cross sections of ^{208}Pb and natural lead is 3 - 4 orders of magnitude. This allows us to hope that with an increase of ^{208}Pb fraction in the coolant, the parasitic neutron absorption in the coolant will decrease, and we can obtain a gain in the length of the campaign for the same initial reactivity margin.

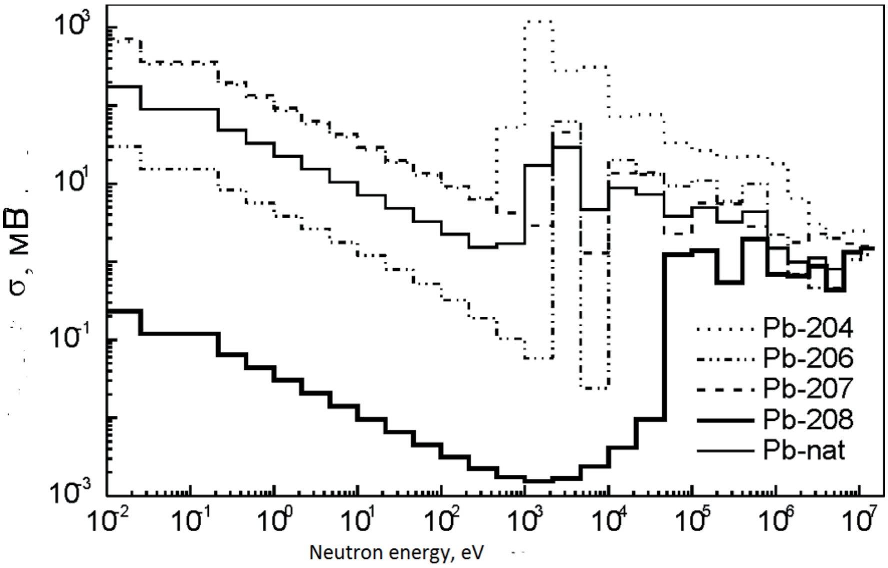

Figure 4: Microscopic cross sections of radiation capture of neutrons by stable lead isotopes and a natural mixture of lead isotopes, ^{nat}Pb, based on the ENDF / BVII.0 library, presented in the 28 group partition of BNAB-93.

3. Results

Some calculations were carried out for a homogeneous and heterogeneous reactor core model using the MCNP [12] and VisualBurnOut for burn up calculations [13]. Table. 4 and Fig. 5 shows the values of Keff during the campaign for the homogeneous model 1 of the RBEC-M reactor in comparison with the results obtained for various calculation programs.

Fig. 6 shows the change in the effective multiplication factor during the campaign for a homogeneous model of the RBEC-M reactor, obtained by the authors of this work for models 1 and 3. It means that the replacement of natural lead with ^{208}Pb will reduce the loading of fissile nuclides and, apparently, increase the campaign.

Results, presented in Table 5, also show the possibility of reducing the fuel loading in the heterogeneous case compared with the homogeneous one and, perhaps, increasing in the duration of the campaign.

For a heterogeneous reactor model, campaigns with different coolant compositions (models 1-5) were calculated. The results are given in Table. 6 and in Fig. 7.

When comparing the calculations for the homogeneous and heterogeneous model 1 of the reactor, the difference between the values of Keff is 1.53% at the end of the campaign. The results of the calculations are given in Table. 5.

Table 4: The dependence of Keff on time in the homogeneous model 1 of the RBEC-M reactor obtained by various authors (data from [4]).

	ANL		BARC	Gidropress		IPPE	RRC KI	Данная работа	TokyoTech
	Used software packages								
Time, days	DIF3D	TWODANT	ERANOS 2.0	DIFRZ	KINRZ	DIFRZ	MCNP5	MCNP/ VBO	Original
0	0.9978	0.9994	0.9950	1.0076	1.0084	0.9944	1.0038	0.9952 +/- 0.0004	1.0104
300	1.0038	1.0041	0.9979	1.0093	1.0093	0.9973		1.0055 +/- 0.0004	1.0150
600	1.0065	1.0073	1.0005	1.0110	1.0110	0.9996		1.0102 +/- 0.0004	1.0185
900	1.0079	1.0090	1.0022	1.0117	1.0119	1.0007	1.0122	1.0125 +/- 0.0004	1.0207
1200	1.0081	1.0096	1.0029	1.0102	1.0132	1.0008		1.0146 +/- 0.0004	1.0220
1600	1.0073	1.0088	1.0026	1.0111	1.0122	1.0000		1.0152 +/- 0.0004	1.0222
1800	1.0063	1.0079	1.0019	1.0102	1.0113	0.9985	1.0102	1.0139 +/- 0.0004	1.0218

Table 5: Dependence of Keff on time for a homogeneous and heterogeneous model of the RBEC-M reactor.

Time, days	0	300	600	900	1200	1500	1800
Homogeneous model 1	0.9952 +/-0.0005	1.0055 +/-0.0005	1.0102 +/-0.0005	1.0125 +/0.0005	1.0146 +/- 0.0005	1.0152 +/-0.0005	1.0139 +/-0.0005
heterogeneous model 1	1,0107 +/-0.0005	1,0212 +/-0.0005	1,0264 +/-0.0005	1,0312 +/-0.0005	1,0349 +/-0.0005	1,0352 +/-0.0005	1,0354 +/-0.0005

We also study the effect of replacing natural lead by ^{208}Pb by the value of the reproduction coefficient. The results of calculations showed an increase in the reproduction rate by about...% compared to the original version.

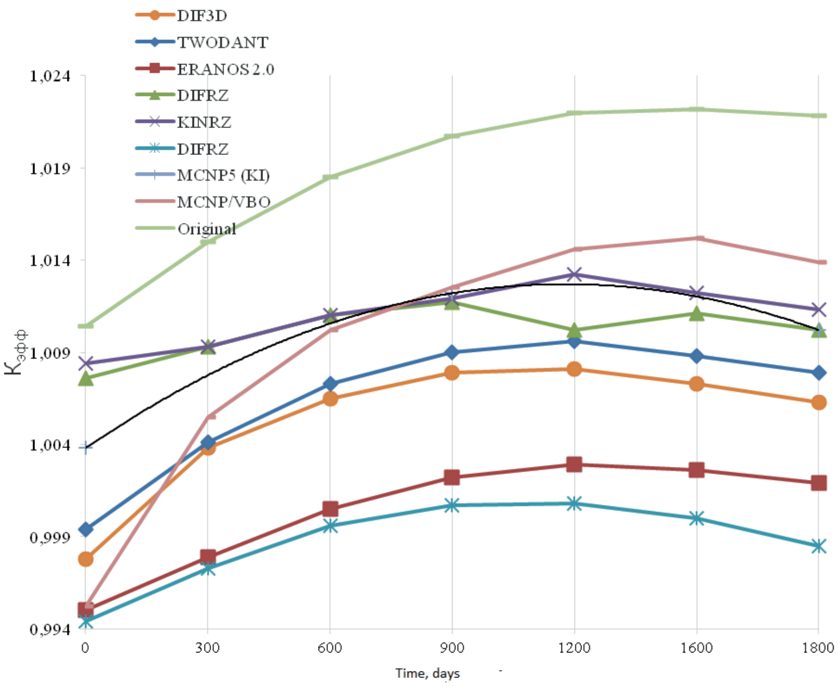

Figure 5: Dependence of the value of Keff on time in the homogeneous model 1 of the RBEC-M reactor.

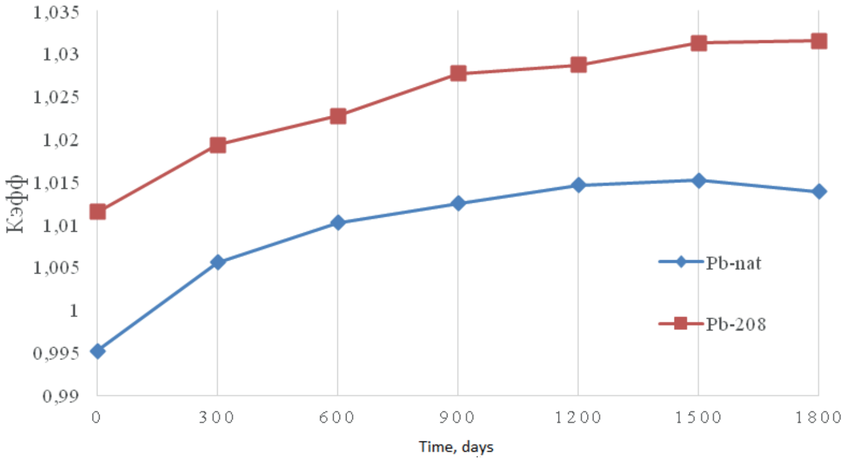

Figure 6: Dependence of Keff on time for homogeneous models 1 and 3 of the RBEC-M reactor.

4. Conclusions

The coolant of the fast neutron reactor, consisting of ^{208}Pb, is very attractive.Replacing the coolant with natural lead to ^{208}Pb or ^{208}Pb with Bi (models 2 and 3) can significantly improve the neutron-physical characteristics of the reactor, in particular, by reducing the initial reactivity margin.Studies of the heterogeneity effect in the reactor model showed an increase of the effective multiplication factor about 1.5% for the end of the campaign.

Table 6: Change in Keff during the campaign in the heterogeneous RBEC-M reactor for various coolant compositions.

Time, days	0	300	600	900	1200	1500	1800
Model 1	1.0107 +/-0.0005	1.0212 +/-0.0005	1.0264 +/-0.0005	1.0312 +/-0.0005	1.034 +/0.0005	1.0352 +/-0.0005	1.0354 +/-0.0005
Model 2	1.0308 +/-0.0005	1.0405 +/-0.0005	1.0477 +/-0.0005	1.0543 +/-0.0005	1.0561 +/-0.0005	1.0583 +/-0.0005	1.0602 +/-0.0005
Model 3	1.0481 +/0.0005	1.0671 +/0.0005	1.0756 +/0.0005	1.0832 +/0.0005	1.0872 +/0.0005	1.0904 +/0.0005	1.0937 +/0.0005
Model 4	0.9586 +/0.0005	0.9696 +/0.0005	0.9780 +/0.0005	0.9834 +/0.0005	0.9883 +/0.0005	0.9903 +/0.0005	0.9919 +/0.0005
Model 5	1.0032 +/0.0005	1.0124 +/0.0005	1.0182 +/0.0005	1.0248 +/0.0005	1.0273 +/0.0005	1.0295 +/0.0005	1.0288 +/0.0005

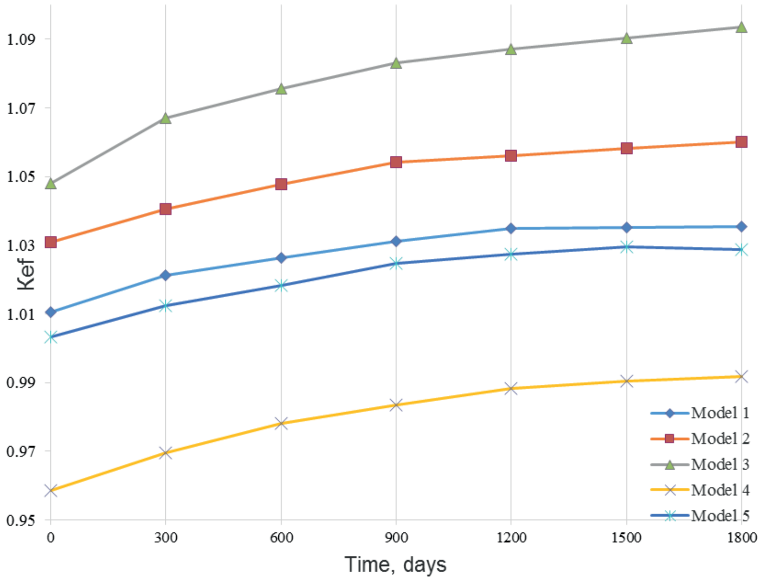

Figure 7: Dependence of Keff on time for the heterogeneous model of the RBEC-M reactor and various coolant composition.

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