

Description of RBEC-M Depletion Benchmark Problem

1. Introduction

The depletion benchmark problem was prepared based on the RBEC-M core, which is a 900 MW(th) lead-bismuth cooled fast reactor concept developed by the Russian Research Centre, “Kurchatov Institute” (RRC KI) [1]. In this reactor concept, the fuel cycle is closed for plutonium and minor actinides except for curium and subsequent minor actinides. The fuel cycle length is 1800 effective full power days (EFPD) and the fuel resides in the core for six partial cycles each of 300 EFPD. The spent fuel is reprocessed and curium isotopes and higher minor actinides are removed in addition to fission products. The reprocessed fuel is replenished with depleted uranium and returned to the core in two years. However, the initial phase of this benchmark exercise is focused on single fuel lifetime analyses for specified fuel management schemes and fissile feeds.

2. Description of the Reactor Model

The benchmark problem was derived from the 900 MW (th) RBEC-M reactor design, having the core configuration shown in Fig.1. Mixed uranium-plutonium nitride fuel ($U_{0.863}+Pu_{0.137}N$) is used, which is composed of reactor-grade plutonium recovered from typical light water reactor spent fuel and depleted uranium with 0.1 wt. % of U-235. The core zones are surrounded by lateral (radial) blankets; the structural material is steel (C, Si, V, Cr, Mn, Fe, Ni, Nb, Mo, W); and the coolant material is lead-bismuth eutectic.

Geometry of the calculation model of the RBEC-M reactor is shown in Fig.2. The model includes 12 physical zones, differing from each other by volume fractions and temperatures of materials. Axial dimensions are specified in mm.

Main dimensions of the physical zones (in cm) are given in Table 1. The temperatures of elements in physical zones are given in Table 2.

The basic version of the RBEC-M depletion benchmark assumes performing the calculations for homogenized zones incorporating elements with different temperatures. The nuclide compositions of fresh fuel and other materials in zones for such homogenized model are given in Table 3 and Table 4.

Recognizing that for some neutronic codes it is impossible to specify isotope data with different temperatures in a single zone, an optional heterogeneous model was developed with core and blanket zones represented by cells shown in Fig.3 with cell parameters given in Table 5. In this optional model, the structure of each zone is represented by a single cell.

There are 4 materials used in RBEC model: 1 – fuel in core, 2 – fuel in blanket, 3 – steel and 4 – coolant. Accepted nuclear densities of these materials are given in Table 6. Homogenized nuclear densities in zones can be obtained as follows:

$$RHO_{\text{homogen}}(n, i) = RHO_{\text{accept}}(n, i) * EPS(m, n),$$

where

n – zone number; i – nucleus number; m – material type number;
 $RHO_{\text{accept}}(n, i)$ – accepted nuclear density of nucleus i in zone n ;
EPS – volume fraction of material m in zone n (see Table 7).

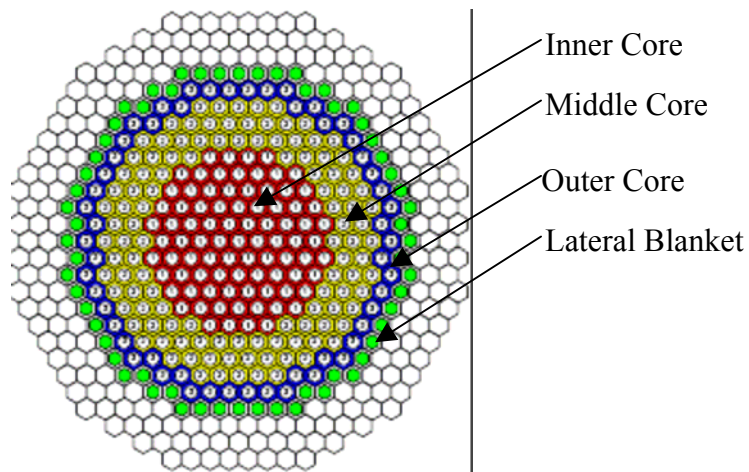


Fig.1 Actual core configuration of the 900 MW (th) RBEC-M reactor

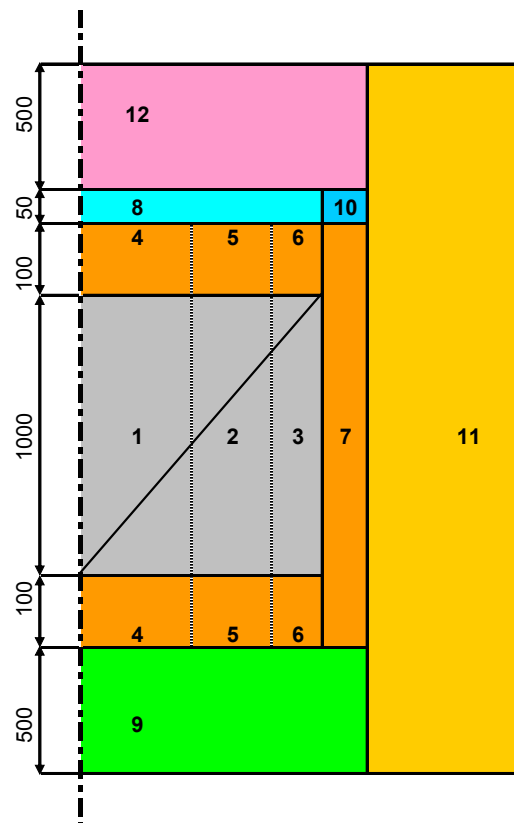


Fig.2. Geometry of calculation model of the RBEC-M reactor.

Table 1. Dimensions of physical zones of RBEC-M reactor model, cm

Physical zone	#	Inner radius	Outer radius	Height
Core-1	1		86.163	100
Core-2	2	86.163	131.837	100
Core-3	3	131.837	148.652	100
Axial blanket of core-1	4		86.163	10
Axial blanket of core-2	5	86.163	131.837	10
Axial blanket of core-3	6	131.837	148.652	10
Lateral blanket	7	148.652	165.342	120
Top of fuel assemblies (FA)	8		148.652	5
Gas plenum	9		165.342	50
Top of assemblies of lateral blanket	10	148.652	165.342	5
Downcomer	11	165.342	211.262	225
Chimney	12		165.342	50

Table 2. Temperatures of elements in physical zones of RBEC-M reactor model, K

Physical zone	#	Fuel	Steel	Coolant
Core-1	1	1200	800	700
Core-2	2	1100	800	700
Core-3	3	1000	800	700
Axial blanket of core-1	4	900/700*	800/600*	800/600*
Axial blanket of core-2	5	900/700*	800/600*	800/600*
Axial blanket of core-3	6	900/700*	800/600*	800/600*
Lateral blanket	7	700	600	600
Top of fuel assemblies (FA)	8		800	800
Gas plenum	9		600	600
Top of assemblies of lateral blanket	10		600	600
Downcomer	11		700	700
Chimney	12		800	800

* - in top/bottom parts of physical zone

Table 3. Nuclear densities in homogenized zones, 1/barn·cm

Physical zone	Core-1	Core-2	Core-3	Axial blanket-1	Axial blanket-2	Axial blanket-3
Zone No. in Fig. 2	1	2	3	4	5	6
<i>Fuel</i>						
U-235	6.42536E-06	7.61116E-06	1.05343E-05	7.47095E-06	8.84971E-06	1.22485E-05
U-238	6.35962E-03	7.53328E-03	1.04265E-02	7.36921E-03	8.72919E-03	1.20817E-02
Pu-238	1.33524E-05	1.58166E-05	2.18910E-05			
Pu-239	6.07226E-04	7.19290E-04	9.95539E-04			
Pu-240	2.43311E-04	2.88214E-04	3.98905E-04			
Pu-241	8.31945E-05	9.85480E-05	1.36396E-04			
Pu-242	4.92603E-05	5.83513E-05	8.07615E-05			
Am-241	8.08633E-06	9.57866E-06	1.32574E-05			
N-14	4.96797E-04	5.88481E-04	8.14492E-04	4.97216E-04	5.88976E-04	8.15178E-04
N-15	6.87368E-03	8.14221E-03	1.12693E-02	6.87947E-03	8.14907E-03	1.12788E-02
<i>Coolant</i>						
Bi-209	1.04654E-02	9.59466E-03	7.46809E-03	1.04654E-02	9.59466E-03	7.46809E-03
Pb-206	2.06859E-03	1.89648E-03	1.47615E-03	2.06859E-03	1.89648E-03	1.47615E-03
Pb-207	1.89696E-03	1.73913E-03	1.35367E-03	1.89696E-03	1.73913E-03	1.35367E-03
Pb-208	4.49772E-03	4.12351E-03	3.20957E-03	4.49772E-03	4.12351E-03	3.20957E-03
<i>Structure material</i>						
C	7.25829E-05	7.75886E-05	8.69743E-05	7.25829E-05	7.75886E-05	8.69743E-05
Si	2.23105E-04	2.38491E-04	2.67341E-04	2.23105E-04	2.38491E-04	2.67341E-04
V	3.74360E-05	4.00178E-05	4.48587E-05	3.74360E-05	4.00178E-05	4.48587E-05
Cr	1.15270E-03	1.23220E-03	1.38125E-03	1.15270E-03	1.23220E-03	1.38125E-03
Mn	6.44665E-05	6.89124E-05	7.72486E-05	6.44665E-05	6.89124E-05	7.72486E-05
Fe	8.22862E-03	8.79611E-03	9.86016E-03	8.22862E-03	8.79611E-03	9.86016E-03
Ni	6.03452E-05	6.45069E-05	7.23102E-05	6.03452E-05	6.45069E-05	7.23102E-05
Nb	1.75942E-05	1.88076E-05	2.10827E-05	1.75942E-05	1.88076E-05	2.10827E-05
Mo	4.25946E-05	4.55322E-05	5.10401E-05	4.25946E-05	4.55322E-05	5.10401E-05
W	1.92638E-05	2.05924E-05	2.30834E-05	1.92638E-05	2.05924E-05	2.30834E-05

Table 4. Nuclear densities in homogenized zones, 1/barn·cm

Physical zone	Lateral blanket (LB)	Top of fuel assemblies	Gas Plenum	Top of LB assemblies	Downcomer	Chimney
Zone No. in Fig. 2	7	8	9	10	11	12
<i>Fuel</i>						
U-235	1.05171E-05					
U-238	1.03738E-02					
N-14	6.99943E-04					
N-15	9.68440E-03					
<i>Coolant</i>						
Bi-209	9.46070E-03	9.52768E-03	9.52768E-03	9.46070E-03	1.50701E-02	1.66609E-02
Pb-206	1.87001E-03	1.88324E-03	1.88324E-03	1.87001E-03	2.97877E-03	3.29320E-03
Pb-207	1.71485E-03	1.72699E-03	1.72699E-03	1.71485E-03	2.73162E-03	3.01995E-03
Pb-208	4.06593E-03	4.09472E-03	4.09472E-03	4.06593E-03	6.47671E-03	7.16036E-03
<i>Structural material</i>						
C	5.88172E-05	7.75886E-05	2.22000E-04	5.88172E-05	6.25714E-05	3.12857E-06
Si	1.80792E-04	2.38491E-04	2.38491E-04	1.80792E-04	1.92332E-04	9.61659E-06
V	3.03361E-05	4.00178E-05	4.00178E-05	3.03361E-05	3.22724E-05	1.61362E-06
Cr	9.34084E-04	1.23220E-03	1.23220E-03	9.34084E-04	9.93706E-04	4.96853E-05
Mn	5.22401E-05	6.89124E-05	6.89124E-05	5.22401E-05	5.55745E-05	2.77873E-06
Fe	6.66802E-03	8.79611E-03	8.79611E-03	6.66802E-03	7.09364E-03	3.54682E-04
Ni	4.89004E-05	6.45069E-05	6.45069E-05	4.89004E-05	5.20217E-05	2.60109E-06
Nb	1.42574E-05	1.88076E-05	1.88076E-05	1.42574E-05	1.51674E-05	7.58370E-07
Mo	3.45163E-05	4.55322E-05	4.55322E-05	3.45163E-05	3.67195E-05	1.83598E-06
W	1.56104E-05	2.05924E-05	2.05924E-05	1.56104E-05	1.66068E-05	8.30338E-07
B-10			5.08102E-04			
B-11			6.95431E-05			

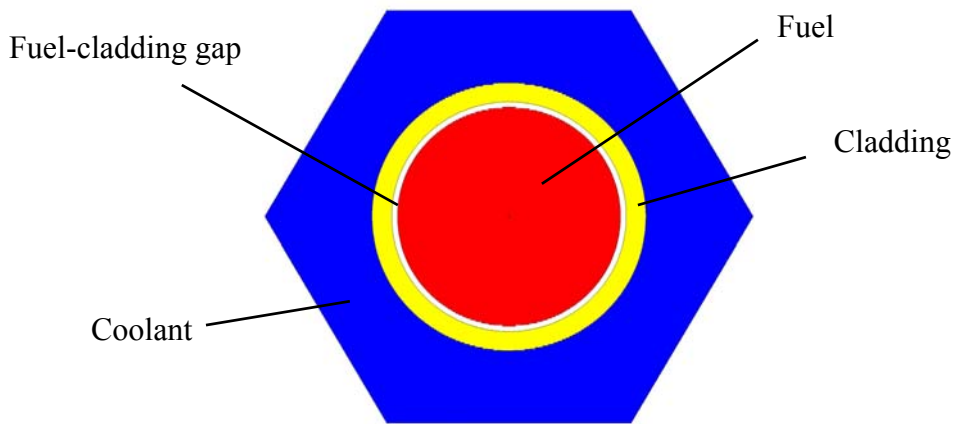


Fig.3. Cell geometry for the optional heterogeneous model

Table 5. Main parameters of RBEC-M core

	Core 1, Axial blanket 1	Core 2, Axial blanket 2	Core 3, Axial blanket 3	Lateral Blanket
Fuel rod pitch in fuel assembly, mm	10.8			15.3
Fuel rod pitch-to-diameter ratio	1.54	1.44	1.26	1.39
Fuel pellet outer diameter, mm	5.7	6.2	7.2	9.7
Radial fuel-clad gap width, mm	0.15			0.10
Fuel rod cladding thickness, mm	0.5			
Outer cladding diameter, mm	7.0	7.5	8.6	11.0

Table 6. Nuclear densities in heterogeneous cell components, 1/barn·cm

Nuclide	Cores	Blankets
<i>Fuel</i>		
U-235	2.75767E-05	3.20642E-05
U-238	2.72945E-02	3.16275E-02
Pu-238	5.73064E-05	
Pu-239	2.60612E-03	
Pu-240	1.04425E-03	
Pu-241	3.57058E-04	
Pu-242	2.11418E-04	
Am-241	3.47053E-05	
N-14	2.13218E-03	2.13397E-03
N-15	2.95008E-02	2.95256E-02
<i>Coolant</i>		
Bi-209	1.67446E-02	
Pb-206	3.30974E-03	
Pb-207	3.03513E-03	
Pb-208	7.19634E-03	
<i>Structural material</i>		
C	6.25714E-04	
Si	1.92332E-03	
V	3.22724E-04	
Cr	9.93706E-03	
Mn	5.55745E-04	
Fe	7.09364E-02	
Ni	5.20217E-04	
Nb	1.51674E-04	
Mo	3.67195E-04	
W	1.66068E-04	

Table 7. Volume fractions of materials in physical zones of RBEC-M reactor

Zone number	Physical zones	Materials			
		Material Number	1	2	3
		Core Fuel	Blanket Fuel	Steel	Coolant
1	Core-1	0.233		0.116	0.625
2	Core-2	0.276		0.124	0.573
3	Core-3	0.382		0.139	0.446
4	Axial blanket of core-1		0.233	0.116	0.625
5	Axial blanket of core-2		0.276	0.124	0.573
6	Axial blanket of core-3		0.382	0.139	0.446
7	Lateral blanket		0.328	0.094	0.565
8	Top of Fuel Assemblies			0.124	0.569
9	Gas plenum			0.124	0.569
10	Top of assemblies of lateral blanket			0.094	0.565
11	Downcomer			0.100	0.900
12	Chimney			0.005	0.995

2.1 Depletion modes for calculation

Three different depletion problems are specified for the benchmark as follows:

Mode.1: Burn-up cycle consists of 1800 effective full-power days.

Mode.2: Burn-up cycle consists of 900 effective full-power days.

Mode.3: Fuel cycle consists of six partial fuel cycles of 300 effective full-power days each. Reactor is shut down for refueling for 60 days. During refueling, 1/6 mass part of fuel and fission products in core and blanket zones is removed and fresh fuel composition is added.

The pattern of data preparation for Mode.3 calculation is as follows:

- Cycle “ i ” begins with initial composition of core zones and blanket zones $RHO1(i,n)$, where RHO is nuclear concentration of heavy metals and fission products in zone “ n ” and cycle “ i ”;
- After 300 effective full-power days, the composition becomes $RHO2(i,n)$, and after 60 days of cooling the composition becomes $RHO3(i,n)$;
- Initial composition for the next cycle “ $i+1$ ” is calculated as follows:

$RHO1(i+1,n) = RHO3(i,n)*5/6 + RHO(0,n)*1/6$, where “ i ” is cycle number, “ n ” is zone index, and $RHO(0,n)$ is fresh composition in zone “ n ”.

The reactor thermal power for depletion calculation in Modes 1, 2, and 3 is 900 MW (th).

2.2 Functionals to be calculated

The requested functionals are as follows:

- For reactor depletion Modes 1 and 2;
In two reference points: beginning of life and end of life:
 - k_{eff}
 - axial and radial power distributions in the core*
 - power peaking factors in the core zones
 - volume averaged neutron spectra in the core zones
 - k_{inf} in the core central zone.

- For depletion Mode 3:
For each of the six cycles in two reference points: beginning of irradiation and end of irradiation:
 - k_{eff}
 - axial and radial power distributions in the core*
 - power peaking factors in the core zones
 - volume averaged neutron spectra in the core zones
 - k_{inf} in the core central zone

*Radial power distributions are to be calculated in two planes: in the core mid-plane and near the core top (45cm above the core mid-plane). Axial power distributions are to be calculated in the radial centre of each core zone.

Optionally, fueled core leakage = integral of fission production minus integral of absorption could be calculated for beginning of life and end of life in Modes 1 and 2.

REFERENCES

1. P. Alekseev, A. Vasiliev, K. Mikityuk, S. Subbotin, P. Fomichenko, T. Schepetina. "Lead-bismuth reactor RBEC: optimization of conceptual decisions", Preprint IAE-6229/4, 2001.