Study on Physics Characteristics of Th-U Fuel in Long-cycle Core

YU Ganglin and WANG Kan*
Department of Engineering Physics, Tsinghua University,
Beijing, 100084, P. R. China

Abstract

Based on the investigation of recent development of the long-life small nuclear power systems in the world, this paper puts forward a new concept of building a long-life reactor core with Thorium-Uranium fuel and Lead-Bismuth coolant and conducts a series of research on the characteristics of the Th-U fuel. In the physics design of a long-life reactor, it is important to keep a small reactivity swing with burnup and a deep burnup core, as well as negative temperature and void reactivity coefficient. The program MCBurn are used in the calculation of a pin cell model with different initial driver fuel, p/d ratio, enrichment and fuel type to obtain some physical results such as neutron spectrum, the reactivity swing with burnup and initial conversion ratio, etc. Based on the analysis of these results, this paper concludes some physical requirements of a long-life reactor core and constructs a preliminary core design with some safety parameters such as void reactivity coefficient and other results.

KEYWORDS: Long-life core, Th-U fuel, Pb-Bi coolant, MCBurn

1. Introduction

This paper describes a new long-life reactor design concept based on the use of thorium and uranium fuel and some research work of Th-U fuel long-cycle core. First we introduce simply the development of the small long-life nuclear energy system concept, thorium-uranium fuel and lead-bismuth coolant. Through the analysis of physics characteristics of a pin-cell model, this paper concludes the advantages and characteristics of the Th-U fuel in fast neutron spectrum environment. We make a series of calculations on one simple long-life reactor core model and get some physical results of this model, including the reactivity swing, the void coefficient and the power distributions.

2. Small long-life reactor and Th-U fuel

Small modular nuclear energy system is an exciting research field now, this type of system often includes the characters: long-cycle core design, low running and maintenance costs, high

---

* Corresponding author, Tel. 86-10-62783087, Fax. 86-10-62782658,
E-mail: wangkan@tsinghua.edu.cn

capacity factor, high safety and reliability, design for special demand, high proliferation resistance. Among the existing long-life reactor concepts, 4S[1](Super Safe, Small and Simple) of Japan, ENHS[2] from U.S., SVBR-75/100[3] from Russia are the most representative designs.

In the design of ultra-long life core, a fast neutron spectrum and U-Pu fuel are applied to get a higher conversion ratio (CR) for higher fuel burnup and less reactivity swing, which require a smaller pitch-to-diameter (P/D) ratio and utilization of U-Pu-Zr metallic fuel to get a harder neutron spectrum. On the other hand, the Th-U fuel is a good choice. The change of the effective number of neutrons released per absorption of U233 is smaller compared with that of U235 or Pu239 in certain energy range, which makes U233 a type of good fuel to be applied in intermediate neutron spectrum condition. When Th-U fuel is used in fast reactor, it's easier to get a negative void reactivity coefficient. A larger P/D ratio in fuel assembly can be used to improve the natural circulation ability, which will be beneficial to some thermal-hydraulics and safety considerations. The oxide fuel can also be used in this fast reactor because the hardened spectrum is not very important in this case.

3. Fissile capability of Th-U fuel in fast neutron spectrum

The research of Th-U fuel has been mainly focused on the thermal reactor before, in fact the U233 has a better fissile capability in fast neutron spectrum. Based on a hexagonal cell model in fast reactor (shown in Fig. 1), this paper discusses the Keff of different fuel in sodium and lead-bismuth coolant conditions, different P/D ratios and enrichments.

From the comparison of the data in Tab. 1 and Tab. 2, it can be concluded that the Pb-Bi coolant is beneficial to improve reactivity. In fast neutron spectrum, the Keff of U233 fuel is larger than those of Pu239 and U235, which shows the U233 has the best fissile capability. The reason is that U233 has the larger effective number of neutrons released per absorption in intermediate neutron spectrum and higher fissile cross section in intermediate and fast neutron spectrum area. The former factor benefits the neutron in the softened fast spectrum area and the latter one reduces the neutron flux in the same power level, which improves the burnup of fuel rod limited by the neutron flux integrated with time. On the other hand, the fissile cross section of Th232 is lower than the U238, which influences the advantage of Th-U fuel.

Table 1: The nuclide fissile capability in sodium coolant conditions

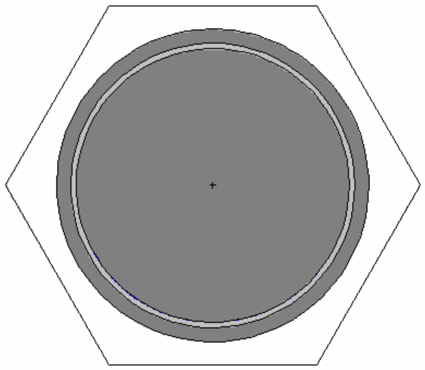
Sodium coolant			
P/D = 1.15 coolant volume ratio = 31.4%			
Enrichment	U5/U8	U3/Th2	Pu9/U8
20%	1.28825	1.50200	1.51791
15%	1.13933	1.30898	1.32285
10%	0.94676	1.04505	1.06424
P/D = 1.5 coolant volume ratio = 59.7%			
Enrichment	U5/U8	U3/Th2	Pu9/U8

20%	1.15453	1.35006	1.34520
15%	1.02605	1.15751	1.15527
10%	0.84878	0.92510	0.93394
P/D = 1.8 coolant volume ratio = 72.01%			
Enrichment	U5/U8	U3/Th2	Pu9/U8
20%	1.03377	1.21027	1.19357
15%	0.90723	1.03361	1.02021
10%	0.74482	0.82077	0.81864

Table 2: The nuclide fissile capability in lead-bismuth coolant conditions

Lead-Bismuth Coolant				
P/D = 1.15 coolant volume ratio = 31.4%				
Enrichment	U5/U8	U3/Th2	Pu9/U8	Pu9/Th2
20%	1.30016	1.51092	1.53793	1.41335
15%	1.15641	1.31454	1.33701	1.18378
10%	0.95727	1.05106	1.07354	0.89645
P/D = 1.5 coolant volume ratio = 59.7%				
Enrichment	U5/U8	U3/Th2	Pu9/U8	Pu9/Th2
20%	1.19047	1.40642	1.41707	1.28116
15%	1.04869	1.21258	1.21016	1.06066
10%	0.84884	0.95592	0.95126	0.80121
P/D = 1.8 coolant volume ratio = 72.01%				
Enrichment	U5/U8	U3/Th2	Pu9/U8	Pu9/Th2
20%	1.08808	1.29552	1.28871	1.16403
15%	0.95501	1.11234	1.09115	0.96349
10%	0.76512	0.87127	0.85243	0.72181

Figure 1: The geometry of the hexagonal cell



Pa233 is an important nuclide in the Th-U fuel conversion chain due to its long decay half-life and large neutron absorption cross section, which influences the neutron economics and the generation of U233. The absorption cross section of Pa233 is so much lower in the fast spectrum than in the thermal reactor that can be ignored, but the long half-life will affect the operation of reactor, which will be analyzed below. The Fig. 2 and Fig. 3 describe the reactivity swing and the variation of nuclide concentration of Th-U and U-Pu fuel in the same enrichment and specific power conditions. The process includes three parts: run 400 days with full power, shutdown and decay 150 days and then restart. It can be concluded in U-Pu fueled reactor the reactivity swing is lower than the Th-U fueled reactor, because the nuclides in the U-Pu chain have short half-life and accumulate a little amount, when the reactor shutdown, the mass of Pu239 will saturate rapidly. In the Th-U fueled reactor, the Pa233 will accumulate a great amount and it will convert to U233 slowly after shutdown, which brings the sustaining increasing of reactivity. The problem should be seriously considered in the actual reactor operation.

Figure 2: Evolution of Keff of Th-U fueled core in shutdown process

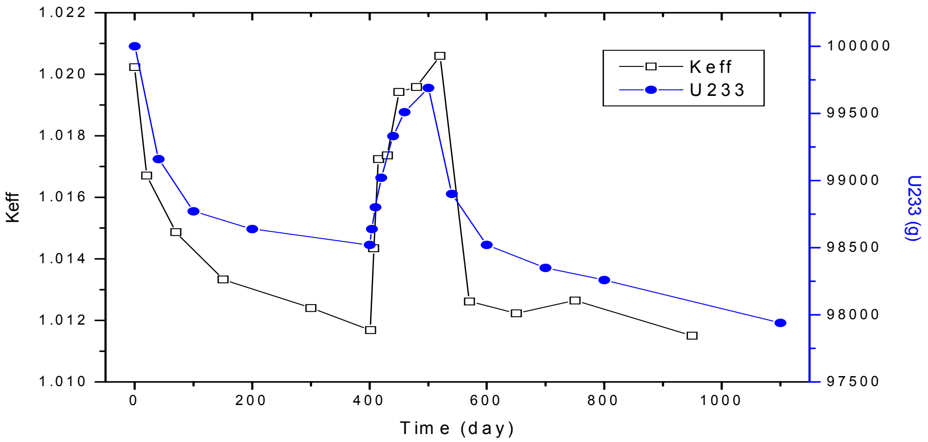
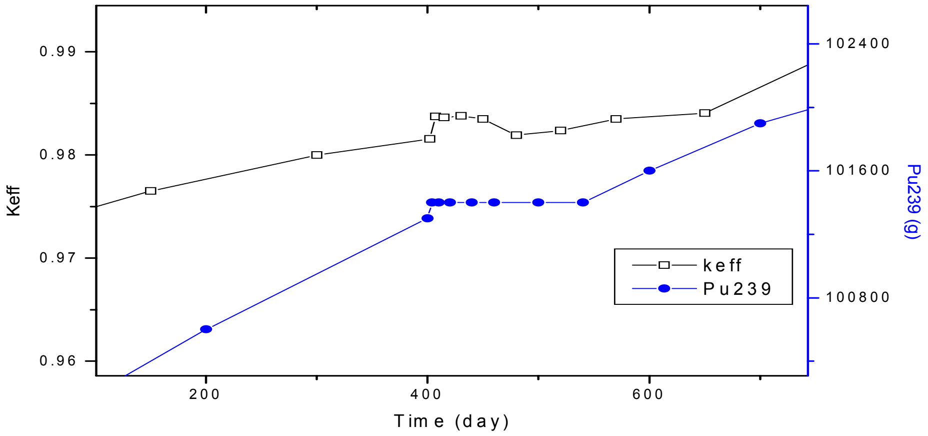


Figure 3: Evolution of Keff of U-Pu fueled core in shutdown process



4. Th fuel in the design of long-life core

In the design of ultra-long life core, higher fuel burnup and less reactivity swing are two of the most important factors in reactor physics. A large burnup reactivity lost will restrict the core design. The small long-life reactor is not a kind of breeder reactor and the key of long-life is generating enough fissile nuclide to compensate the lost reactivity with burnup. In the design of U-Pu fueled reactor a larger conversion ratio (>1) is applied to keep the reactivity swing about zero, which needs a hardened spectrum. A small core size in small reactor benefits a negative void reactivity coefficient but the neutron leakage will reduce the breeder efficiency. As a result, it's not easy in both physics and safety to design a long-life core with U-Pu fuel.

Combining the spent Pu and the Thorium fuel together, it will be suitable to the long-life reactor design. With the application of the Pu-Th fuel, we can design a reactor with near zero reactivity swing even if the conversion ratio lower than 1, because the new generated U233 will compensate the lost of Pu239. If the fuel type, enrichment, cell geometry and other parameters are carefully selected, the reactivity swing of reactor will keep zero in very high burnup condition.

5. Burnup characteristics of Th-U fuel cell

The normal life of long-life reactor is more than 10 years, even reaches to 30 years. Based on a pin-cell model, we discuss the physics characteristics of Th-U fuel in the intermediate to fast neutron spectrum and high burnup conditions. The parameters of calculation model are similar to the typical fast reactor except for the square geometry (shown as Fig. 4). The calculation tool is the code MCBurn[4,5].

Fig. 5 shows the neutron spectrum of the Th-U fuel in Na or Pb-Bi coolant with different geometry, the spectrum will be softened when the P/D ratio increases, especially with the Na coolant. Fig. 6 shows the evolution of Keff of Th-U fuel with burnup in Pb-Bi coolant and with the different geometry, when the P/D ratio becomes larger, the reactivity will decrease rapidly but the breeding capability increases.

At the beginning of this research work, the driver fissile nuclide is U233, which is impossible in actual design. The available drive fuels include: high enrichment U235 fuel, the spent Pu fuel from PWR and the nuclear weapon grade Pu fuel. The fuel physics characteristics have much difference when the driver fuel changes. From the Fig. 7, we can see the enrichment should improve to keep critical for the lower fissile capability. The reactivity swing of Pu-driven reactor is the smallest.

Figure 4: The geometry of the quadrate cell

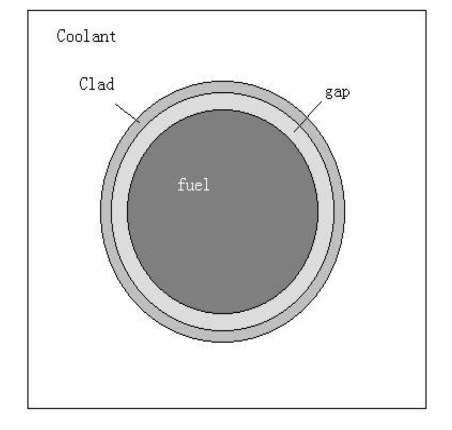


Figure 5: The spectrum of Th-U fuel in different conditions

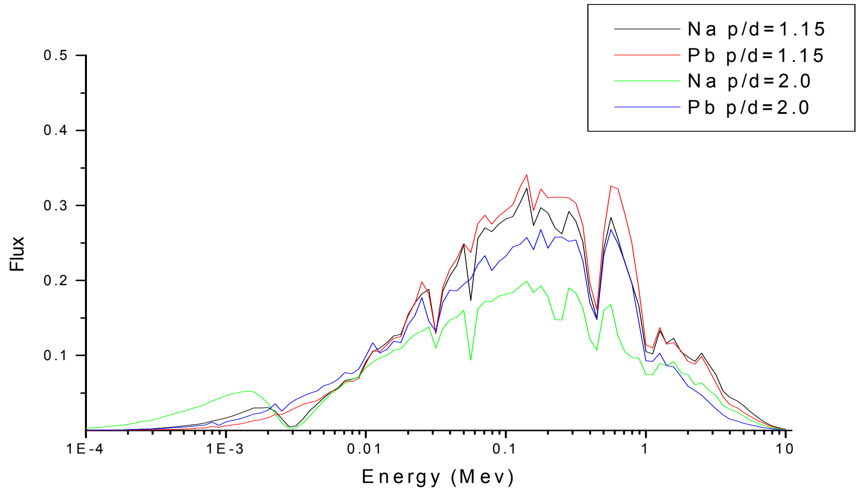


Figure 6: Evolution of Keff of Th fuel with burnup in Pb-Bi coolant

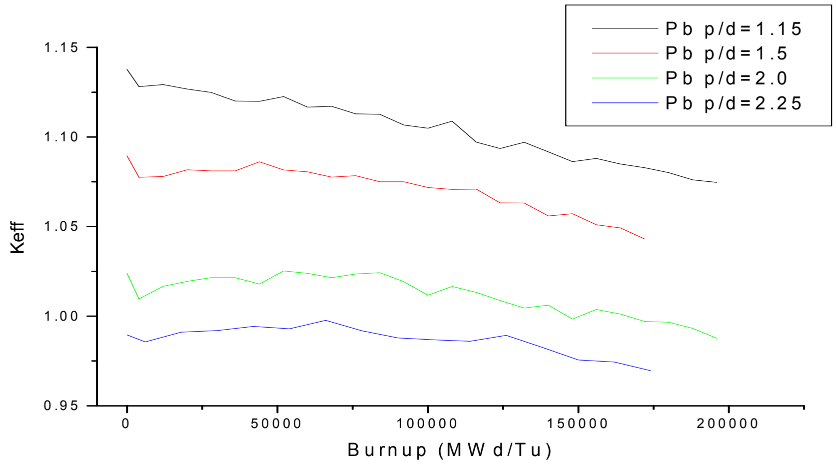
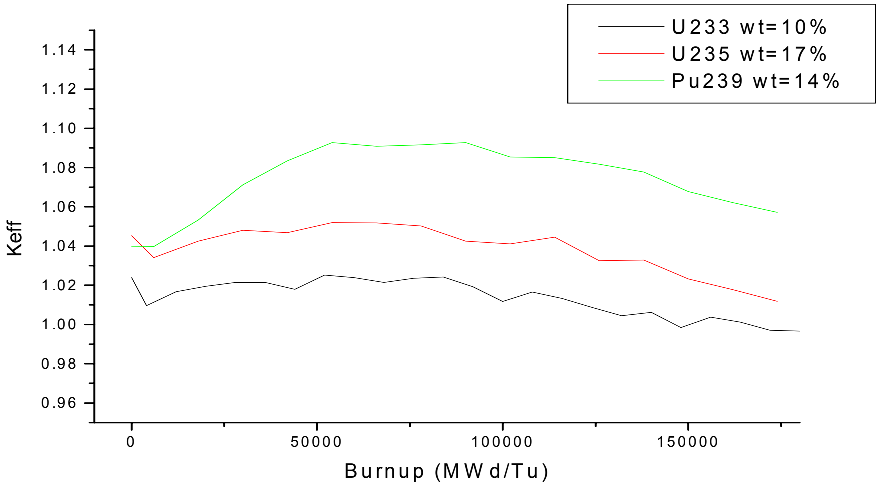


Figure 7: Evolution of Keff of Th fuel with burnup in different drive fuels



6. Physics characteristics of a simple core model

Based on the research work of pin cell, we build a simple core model with Th-U fuel and Pb-Bi coolant, shown in Fig. 8. The central area is made of Th-U fuel with large P/D ratio, in the center of the core is the control rod area. The shell of the reactor is made of SS. When the specific power is 30w/g, the full power of reactor is 450MWt.

Because of the large P/D ratio, the volume of the core model is larger than normal conditions, which decreases the neutron leakage and does harm to the negative void coefficient. We separate the core into 8 parts, calculate the Keff when the coolant in each part is voided and show the results in Tab. 3. It can be concluded that the Th-U fuel and Pb-Bi coolant reactor has a negative void coefficient in every case and the core has a low neutron leakage about 3%.

Fig. 9 shows the Keff evolution of the core with burnup in different fuel, the driver fuel is spent Pu fuel and the fertile nuclides are U238 and Th232, respectively. We can see when U238 is used as fertile nuclide the reactivity swing is larger because the soft spectrum, which influence the breeder ratio in spite of the lower enrichment. When Th232 is used, the enrichment is higher but the reactivity swing is about 1% because the generation of U233 compensates the lost of fissile nuclide Pu239.

Fig. 10 and Fig. 11 show the axial and radial power distribution of the BOL and 100000MWd/THM burnup EOL with spent Pu and Th fuel. The axial and radial power distribution keep same in the reactor operating time, thus the life of the core depends on the limit fast fluence of the cladding of the peaking power fuel rod.

Figure 8: The geometry of the axial and radial cross section of the core

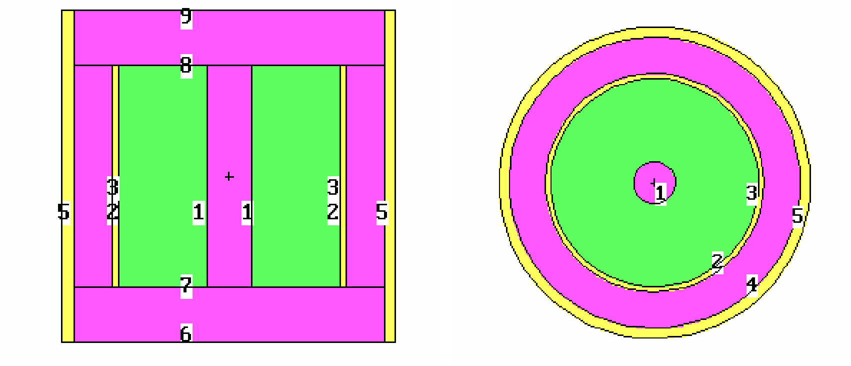


Table 3: the void coefficient of the core model

	Keff	Void coefficient 10^{-5}/% void
Standard core	1.04432	
No neutron leakage	1.07174	
Inner circle coolant voided	1.04377	-0.55
Circle 2 coolant voided	1.04212	-2.2
Circle 3 coolant voided	1.04265	-1.67
Circle 4 coolant voided	1.03629	-8.03
Circle 6 coolant voided	1.03646	-7.86
Outer circle coolant voided	1.03841	-5.91
Full core coolant voided	1.00122	-43.1

Figure 9: Evolution of Keff of the core with burnup in different fuel

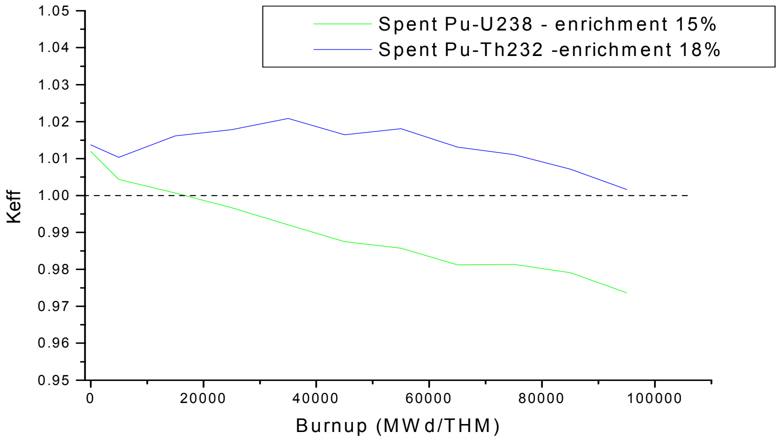


Figure 10: The radial power distribution of the core

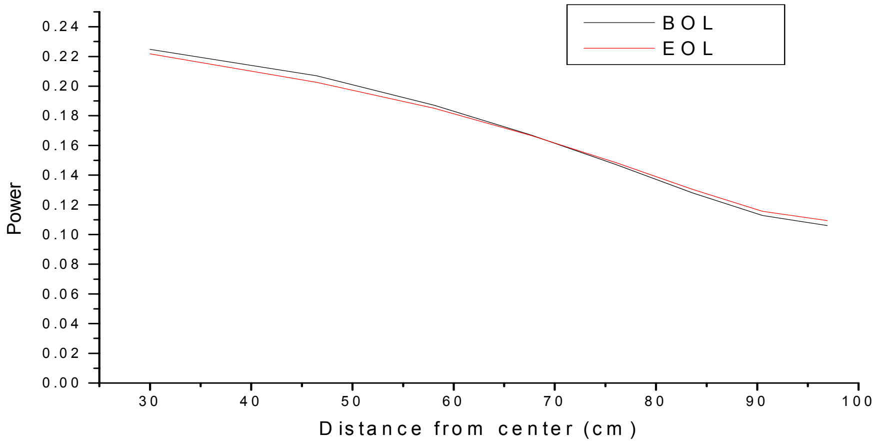
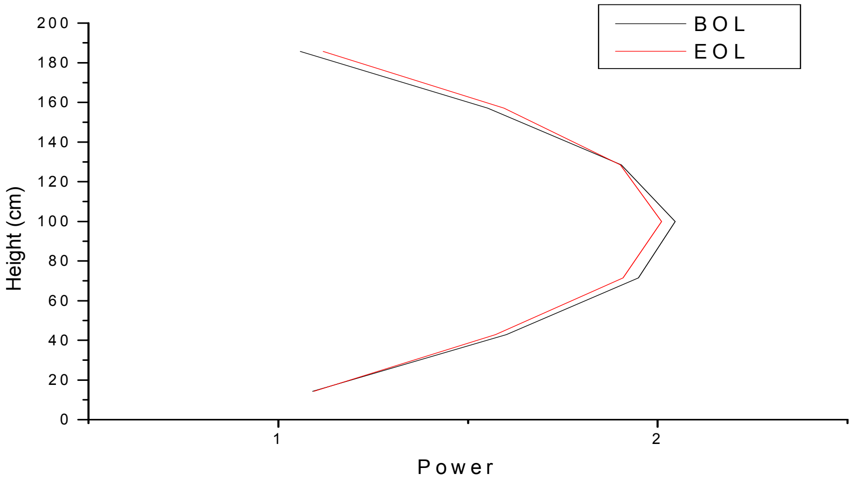


Figure 11: The axial power distribution of the core



7. Conclusion

From the analysis and calculation of the Th-U fuel, we can conclude: Th-U fuel has better physics characteristics in intermediate and fast neutron spectrum; the usage of the Th-U fuel will benefit the design of long-life reactor core and to improve the burnup; The spent fuel Pu can be selected as the driver fuel; It's easy to get a negative void coefficient in a core with Th-U fuel and Pb-Bi coolant. Our next work is to continue the research and complete a full conceptual design of a long-cycle Th-U fueled core.

Reactor. 10th International Conference on Nuclear Engineering, Arlington, VA (2002/4).

2) E. Greenspan et al. The Long-Life Core Encapsulated Nuclear Heat Source (ENHS) Generation IV Reactor. Proc. Int. Cong. on Advanced Nuclear Power Plants (ICAPP), Hollywood, Florida, 2002.
3) A. V. Zrodnikov. Multipurposed Small Fast Reactor SVBR-75/100 Cooled by Plumbum-Bismuth. From Internet.
4) J.F. Briesmeister. MCNP – A General Monte Carlo N-Particle Transport Code[Z]. LA-12625-M. Version 4B. Los Alamos National Laboratory. 1997.
5) Yu Ganglin, WANG Kan, Wang Yuhong. MCBurn - A Coupling Package of Program MCNP and ORIGEN. Nuclear Energy Science and Technology(In Chinese), 2003,37(3):250-254.