Calculation evaluation of multiplying properties of LWR with thorium fuel

I V Shamanin[2], V M Grachev[1], V V Knyshev[2], S V Bedenko[2] and N G Novikova[2]

[1] National Research Nuclear University MEPhI, Moscow, Russian Federation
[2] National Research Tomsk Polytechnic University, Tomsk, Russian Federation

E-mail: shiva@tpu.ru

Abstract. The results of multiplying properties design research of the unit cell and LWR fuel assembly with the high temperature gas-cooled thorium reactor fuel pellet are presented in the work. The calculation evaluation showed the possibility of using thorium in LWR effectively. In this case the amount of fissile isotope is 2.45 times smaller in comparison with the standard loading of LWR. The research and numerical experiments were carried out using the verified accounting code of the program MCU5, modern libraries of evaluated nuclear data and multigroup approximations.

1. Introduction

In Russia at present the technologies connected with implementation of thorium nuclear cycle are innovative, so technically and economically they are not developed, consequently, they are connected with significant financial investments and risks. However, taking into consideration potential possibilities of thorium nuclear cycle, duration of the development and new nuclear technologies implementation phase there is need for works aimed at selection of the optimum alternative of using thorium in both operating and innovative constructions of reactors [1-4].

In works [4,5,11-15] 40 different constructions of low- and average power operating reactors and some innovative engineering solutions, which are being developed and licensed, were considered. Problems of using thorium for high temperature reactors (HTR), heavy water reactors (HWR) and light water reactors (LWR) are being researched. A very important conclusion that implementation of thorium nuclear cycle for fast neutron and light-water reactors is essential and timely has been made. In such reactors there are developed technologies which allow performing modernization of existing constructions of fuel assemblies and substitute traditional uranium fuel with thorium, providing necessary conditions.

BREST-300-OD is a well-developed construction of fast reactors with the power corresponding to low-power reactors in which thorium fuel can be used. This pilot and demonstration construction will become a new advanced model element of nuclear fuel cycle in Russia [1].

In work [3] behaviour of LWR of WWER-1000 type when active core is loaded with fuel assemblies with different types of thorium containing oxide fuel is analyzed. The calculation results showed working efficiency of using thorium in WWER-1000 of production design, as WWER-1000 operates in the open fuel cycle, the operation period and fuel burnup reach the peak value.

Constructions of high-temperature gas cooled nuclear reactors (HTGR) are supposed innovative solutions. In recent decades engineering and construction of modular HTGR of low and average power have been started or resumed [4,5,11-15].

In works [4, 5] calculation researches of low power HTGR were carried out. Physics of the reactor with fuel blocks and fuel pellets of different configurations were studied for the purpose of choosing the most optimum construction of the reactor core and its loading. Calculation results of multiplying properties and fuel burnup depth were shown for the chosen configuration. The research results allowed formulating conception of low power HTGR with the reactor core assembled from fuel blocks of the unified design. The number of fuel blocks and reactor core dimensions should be determined by the value of the reactor power which is required for solving the task-oriented problem, but fuel and fuel blocks will be produced in series (see fig.1).
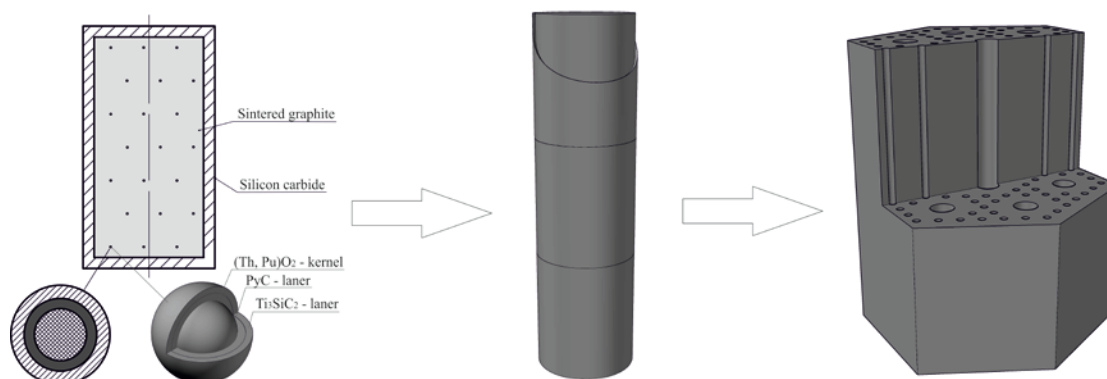

Figure 1. Scheme of fuel unit filling with fuel.

Economical assessment showed that if fuel pellet configuration suggested for HTGR is used in other reactor type, it will allow reducing production costs of the fuel and advancing efficiency of its application.

Therefore calculation evaluation of neutron-physical characteristics of LWR with thorium fuel pellet of HTGR was performed in the work.

2. Calculation model of LWR fuel assembly

Fuel elements for HTGR designed in the form of spheres, cylinders and prisms are made as carbon and graphite matrix composition containing microencapsulated fuel (coated particle fuel, microfuel). Microfuel is fuel kernel from fissionable material with some coating layers.

Various ceramic compositions (PyC, SiC, ZrC, TiC, etc.) and nanolaminates are applied as protective coatings very often [6-10]

The main function of such protective coatings is to retain different gaseous and solid fission products during the irradiation process.

Currently existing technological solutions are aimed at increasing the service life of microfuel by enlarging the number of layers, which in its turn results in the decrease of protective coatings damage rate.

But increase of the number of the layers does not solve the problem of deconfinement and fuel kernel migration at long-term irradiation and high temperature (see fig. 2, 3).
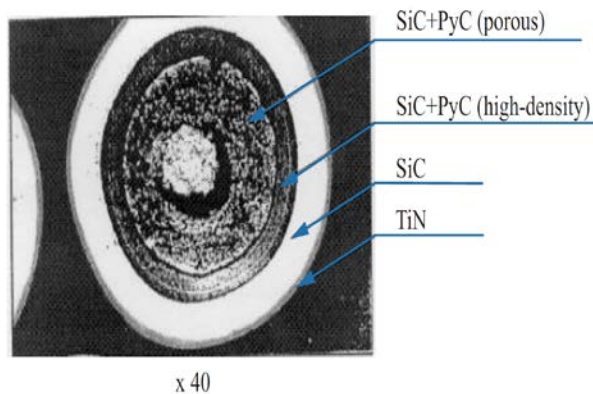
Figure 2. Results of microfuel irradiation with four-layer protective coatings on the basis of PyC-SiC.
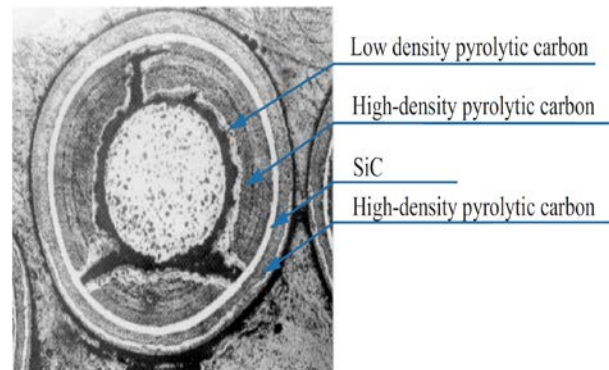
Figure 3. Results of microfuel irradiation with four-protective coatings on the basis of high density PyC-Si.

Thus it becomes evident that revolutionary materials and plating technologies are needed. At present "coated particles" technology is used for forming coatings for spherical fuel kernel [8]. This technology is also applied for cylindrical LWR fuel pellets of standard configuration [9]. However, this method has such disadvantages as low rate of coating deposition (~0.001 μm/s) and processing complexity of coating deposition from a wide range of materials.

Functional coating formation technology by the method of "semifluidized bed" had been developing in Germany for 20 years and the expenses were several billion deutschemarks [10].

This method is very technological as it provides the possibility to control and adjust quality and thickness of the coatings. The main disadvantages of this method are limited range of applied materials (C, SiC) and strict requirements to the continuity of thermodynamic parameters of the media. So surfacing metal coatings by the method of "semifluidized bed" does not seem possible at present.

The technology of coating deposition from different materials (including metallic) on the surface of spherical kernel with the diameter of $(350-800)$ μm and cylindrical pellets with the diameter of $(8-12)$ mm and height of (15) mm was developed at National Research Tomsk Polytechnic University. The possibility to modify properties of surface layers of construction materials is being researched [7].

The method has such an advantage as high rate of the coating process $(\geq 0.003$ μm/s$)$ and it allows forming coatings from metallic materials, as well as from superstrength materials such as diamond [7].

The peculiarity of the material forming the coating in the given case is its structure. It is amorphous and is characterized by increased resistance to the effect of destroying neutron and γ-quantum flux.
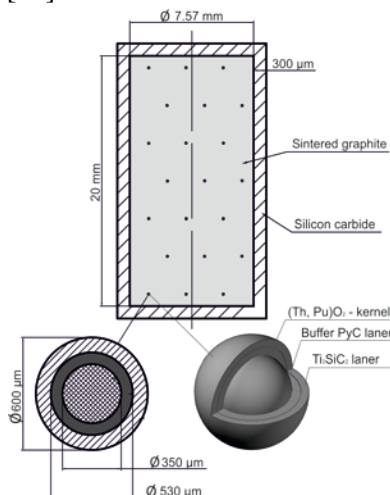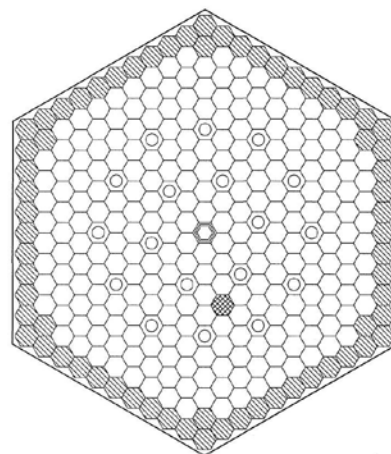
Applied configuration of micro fuel and fuel pellet is presented in fig.1 [4, 5]. Low-density PyC-layer is used for location of gaseous fission products and is the first diffusion barrier which protects the second Ti_3SiC_2-layer from damage. Ti_3SiC_2 possesses excellent mechanical and thermal-physical characteristics and serves as the main power coating and diffusion barrier towards solid fission products. An additional safety barriers formed by a graphite matrix and a functional coating in the form of SiC-layer with the thickness of ~300 μm on the pellet surface. Thorium-plutonium fuel composition is used as fissile isotope. The isotopic composition of military Pu is presented in [16].

Service life irradiations of the fuel pellet of the given configuration show that radiation dimensional changes of the kernel (see Tab. 1), the coatings and the fuel pellet are insignificant, small in absolute magnitude, and structural characteristics are stable (id of the works is RFMEFI59114X0001, 2014). The service life of the fuel pellet towards metals impurities in the kernel is limited by the temperature compatibility of~ 1350 K; radiation stability is limited by the fast fluence of ~$0.6\cdot10^{26}$ m^{-2}; but the pellet is resistant for a short moment up to the fluence of~$2\cdot10^{26}$ m^{-2}.

Table 1. Microfuel and fuel pellet specifications

Specifications	Value
Microfuel type	BISO
Fuel composition	$(Th,Pu)O_2$
Pu/Th composition	50%/50%
Pu isotopic composition (%)	military Pu
Microfule diameter (μm)	600
Fuel kernel diameter (μm)	350
PyC inner coating layer thickness (μm)	90
Ti_3SiC_2 outer coating layer thickness (μm)	35
Average density	
Fuel kernel (g/sm^3)	10.5
PyC (g/sm^3)	1.20
Ti_3SiC_2(g/sm^3)	4.16
Microfuel service life	
Fast fluence (м$^{-2}$)	~$0.6 \cdot 10^{26}$
Temperature (K)	~1250
Fuel pellet	TRISO
Height (m)	0.0202
Diameter (m)	0.00757
SiC protective coating thickness (μm)	300
SiC average density (g/sm^3)	3.20

The fuel pellet and fuel assembly calculation model (see fig. 3,4) was created using program MCU5 (developed by Russian Research Center «Kurchatov Institute») A geometrical module of MCU5 allows simulating 3D systems with geometry of any complexity using the combinatorial approach, which is based on complex systems description by combinations of elementary bodies and surfaces [17].

Figure 3. Microfuel and fuel pellet calculation model.

Figure 4. Fuel assembly calculation model.

2.1. Research methods.

Researches and numerical experiments were carried out using the calculation code of the MCU5 program, modern libraries of evaluated nuclear data (ENDF/B-VII.0, JEFF-3.1.1, JENDL-4.0, ROSFOND, BROND, BNAB, etc.) and multigroup approximations.

The MCU5 program is intended for precision process simulation of neutrons and photons transfer in any types of reactors by analogue and non-analogue Monte-Carlo methods on the basis of evaluated nuclear data, taking into consideration isotopic composition change of reactor materials.

For calculating the reactor life-time the calculation module BURNUP of the MCUP program is used. This module is meant for composition change calculation of fissile and absorbing reactor materials during its life-time. Also the module provides the possibility of calculation prediction of reactor materials nuclide composition and its multiplying properties depending on the fuel burnup. The calculation of reactor isotopic composition change during its life-time is performed at given dependence of average power density on time.

3. Results of neutron-physical researches

In fig. 5 and 6 the results of neutron-physical calculations of the unit cell and the LWR fuel assembly are presented. The calculation evaluation showed the possibility of efficient use of thorium in LWR. . Increased fuel burn-up depths are reached when military Pu is used (see tab.1). In this case the amount of fissile isotope in the fuel pellet with micro fuel is 2.45 times smaller than in the fuel pellet of the series LWR, and the fuel-element life-time is ~1500 effective days.
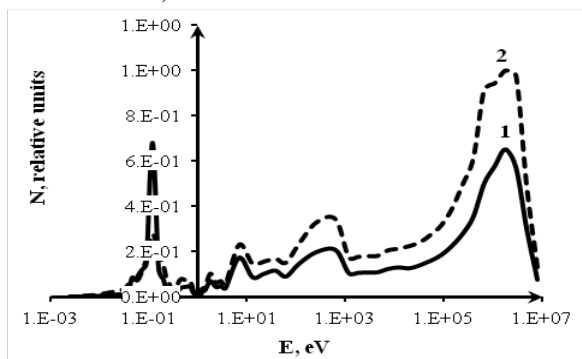

Figure 5. Neutrons spectrum in unit cell fuel portion:1 – fuel pellet with microfuel, 2 – fuel pellet of series LWR.
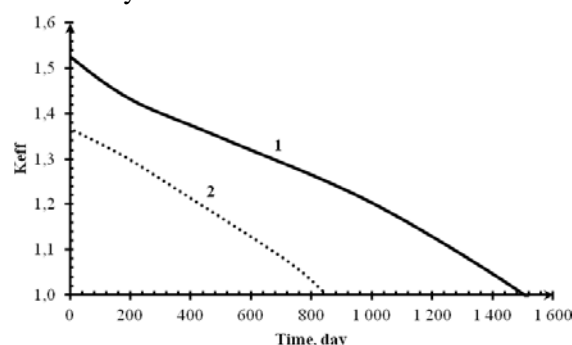
Figure 6. Multiplying properties of fuel assembly: 1 – fuel assembly with HTGR fuel pellet, 2 – fuel assembly with LWR fuel pellet.

4. Conclusion

The results of service life tests of HTGR thorium fuel pellet with the dispersed microfuel (BISO) were presented in the work. Also the results of calculation researches of multiplying properties of the unit cell and the LWR fuel assembly with HTGR fuel pellet were given. The calculation evaluation showed the possibility of using such replacement, because in this case the amount of fissile isotope is 2.45 times smaller compared with standard LWR loading. Increased fuel burn-up depths are reached when military Pu is used. The fuel-element life-time is ~1500 effective days, and the fuel burnup is ~150 GW day/tHM.

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