Conference Paper

Comparison of Different Fuel Compositions for a Research Reactor with Thermal Power of up to 10 MW

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Abstract

In this article the prospect of using carbide fuel in a research reactor for export to countries with developing nuclear power is consider. The choice of a fuel composition for a research reactor is an important part in substantiating of the neutron-physical and economic characteristics of a reactor facility, and is also an important part of the control-dependent self-sustaining fission chain reaction in a nuclear reactor that affects the specifics of management. For reducing the economic component in the design of this reactor core of the research reactor, structural materials and design solutions are used that have extensive experience in domestic power engineering. In this work UO_2-ThO_2 and PuO_2-ThO_2 was selected as the considered fuel compositions. In the course of the study, characteristics were obtained for a burnup of the fuel compositions under study, the initial reserve of reactivity and the duration of the fuel campaign.

Keywords: no-transshipment campaign, research reactors, reactivity margin, delayed neutron fraction, fuel composition

1. Introduction

Presently there is a noticeable interest in research reactors for usage in various areas of science and technology. One of the most actual is the market of radioisopic products in medicine. From the point of view of nuclear medicine, the following isotopes are of interest: ^{90}Y, ^{188}Re, ^{99m}Tc, ^{99}Mo, ^{68}Ga and others. A nuclear reactor with a thermal power of up to 10 MW with a fuel campaign no less than 10 years will allow to reduce the cost of handling fresh and spent nuclear fuel, as well as partially solve the problem of accounting, control and non-proliferation of nuclear materials. The purpose of the present research is to develop the concept of a serial reactor designed to produce radioisotope products, potentially capable to overcome the threshold of commercialization. Due to the fact that the reactor is expected to be operated in countries with low experience in the use of nuclear technologies, one of the most important criteria is the requirement for operation without refueling during a long campaign.

2. Materials and Methods

As the prototype serial reactors VVR and IRT [1] was chosen. The thermal capacity of the reactor is up to 10 MW. The size of the reactor tank is selected from the condition of a low level of activation of its material at the end of the campaign, permitting general industrial reprocessing without burial. The reactor core consists of the shortened fuel assemblies of the VVER-440 reactor [2], which allows organizing their production on existing equipment. The active zone contains 85 shortened fuel assemblies with a beryllium reflector located around the fuel assembly. Reactor core height 156 cm, reactor core diameter 146 cm. Cartogram of the core of a research reactor is shown in Figure 1.

Serpent (PC Serpent) (Finland) [3], which implements the Monte Carlo method, was used for calculation. The Serpent PC uses area geometry to describe complex systems very similar to the MCNP program (USA). This means that the geometry is divided into separate levels that are built independently and can be nested inside each other. This approach allows you to divide complex geometry into simpler parts, which are much easier to build.

The Serpent software package reads neutron interaction data with cores from neutron data libraries in the ACE format. A typical library package contains libraries in the ACE format based on the evaluated neutron data libraries JEF-2.2, JEFF-3.1, ENDF / B-VI.8 and ENDF / B-VII for several temperatures. In addition, the Serpent PC has a built-in algorithm for accounting for the Doppler effect, which allows one to take into account the dependence of neutron interaction cross sections with the medium on its temperature [4].

The use of promising fuel compositions can lead to an increase in the campaign of the reactor. The paper considers two types of fuel for a research reactor: UO_2-ThO_2 and PuO_2-ThO_2. The effect of the choice of the fuel composition on the neutron-physical and thermal-hydraulic characteristics of the core of the research reactor with a capacity of 10 MW is considered.

This type of fuel was previously used in thermal neutron reactors. Table 1 presents light-water reactors that operate with thorium fuel at US nuclear power plants in the last century [5]. In Russia, a study was conducted on the possibility of using thorium fuel in VVER-1000 reactors [6]. It is worth noting the difference in the physical properties of the compounds of uranium, thorium and plutonium (Table 2) [7].

Table 1: Light water reactors working with thorium fuel at US nuclear power plants.

NPP	Type of reactor	Power (thermal), MW	Fuel	Operating period
Indian Point	BWR	60	ThO_2 -UO_2(93% обог. U)	1962-1974
Elk River	PWR	615	ThO_2 -UO_2(93% обог. U)	1964-1968
LWBR	PWR	237	ThO_2 -$^{233}UO_2$	1977-1982

Table 2: Physical properties of uranium, thorium and plutonium compounds.

Properties	ThO_2	UO_2	PuO_2
Mass density, g/m^3	10	10.96	11.5
Fusioning temperature, °C	3300	2760	2400
Thermal conduction at 600 °C, kcal/m^2*h* °C	2.7	3.0	3.0

Table 3: Materials of the reactor core.

Options	Value
Coolant	Water
Moderator	Water
Reflector	Beryllium
Fuel pin cladding	Zr+Nb
Fuel composition 1	UO_2+ThO_2
Volume of UO_2 -fuel in mixture	0.35
Fuel enrichment by ^{235}U	0.195
Fuel composition 2	PuO_2+ThO_2
Volume of PuO2 -fuel in mixture	0.1
Composition of plutonium Pu238/Pu239/Pu240/Pu241/Pu242	0.005/0.6/0.245/0.109/0.041

Table 4: The change in nuclear concentrations (10^{24} nuclei / cm^3) of some heavy isotopes for nuclear fuel campaigns for UO_2-ThO_2 and PuO_2-ThO_2 fuel compositions.

Burnout time, year	Fuel UO_2-ThO_2			Fuel PuO_2-ThO_2		
	^{232}Th	^{233}Pa	^{233}U	^{232}Th	^{233}Pa	^{233}U
0	2.16E-02	0	0	1.99E-02	0	0
1	2.16E-02	1.17E-05	4.3E-06	1.99E-02	7.82E-07	6.48E-06
2	2.16E-02	1.18E-05	9.12E-06	1.99E-02	7.87E-07	1.36E-05
3	2.15E-02	1.19E-05	1.39E-05	1.99E-02	7.90E-07	2.06E-05
4	2.15E-02	1.19E-05	1.87E-05	1.99E-02	7.93E-07	2.75E-05
5	2.15E-02	1.20E-05	2.36E-05	1.99E-02	7.96E-07	3.42E-05
6	2.15E-02	1.20E-05	2.84E-05	1.98E-02	7.99E-07	4.08E-05
7	2.15E-02	1.21E-05	3.32E-05	1.98E-02	8.03E-07	4.72E-05
8	2.15E-02	1.22E-05	3.8E-05	1.98E-02	8.04E-07	5.35E-05
9	2.15E-02	1.22E-05	4.28E-05	1.98E-02	8.08E-07	5.97E-05
10	2.15E-02	1.23E-05	4.76E-05	1.98E-02	8.12E-07	6.58E-05

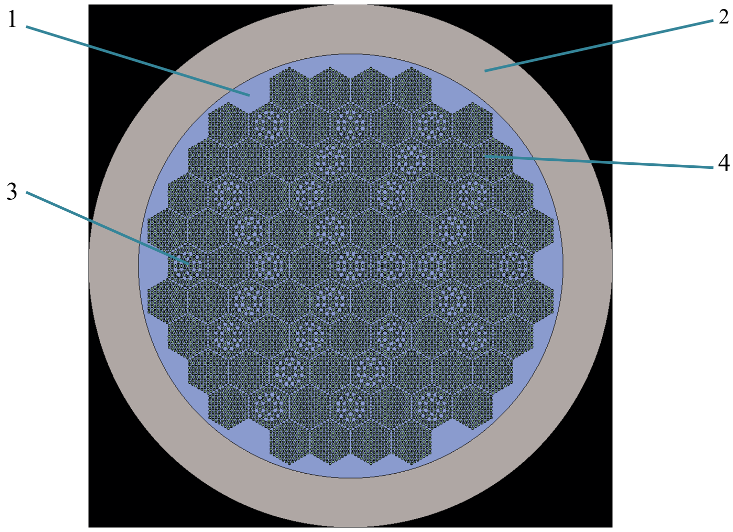

Figure 1: Cartogram of the core of the research reactor. 1 – Moderator; 2 – beryllium reflector; 3 – fuel assembly guide channels; 4 - fuel assembly.

3. Results - Discussion

The preliminary calculations have shown that the fuel should contain 14% UO2 and 86% ThO2 to the research reactor has operated without overload for 10 years at a power of 10 MW. Uranium enrichment by the isotope ^{235}U will be 19.5%. Such enrichment corresponds to IAEA requirements for reactor fuel [9].

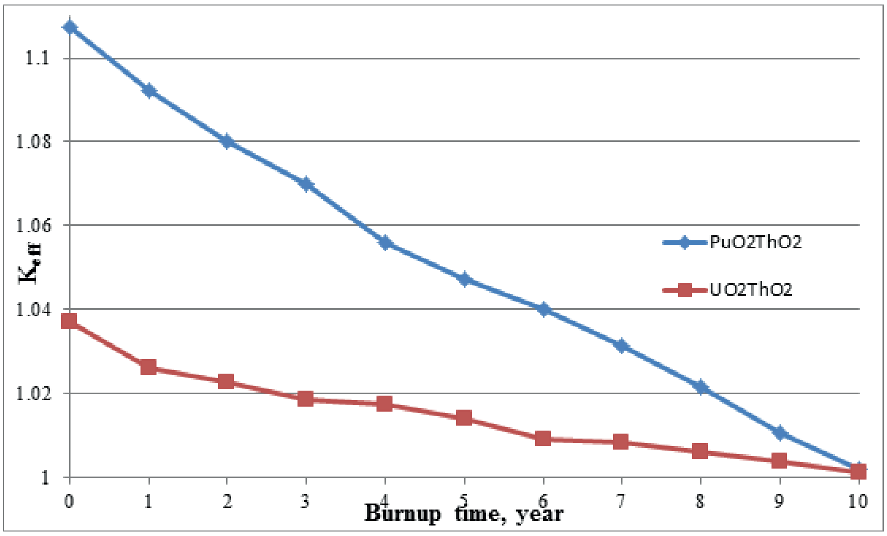

Figure 2: Dependence of the effective multiplication factor of the reactor core of a research reactor on the nuclear fuel campaign for UO_2-$ThO_2$and PuO_2-ThO_2 fuel compositions.

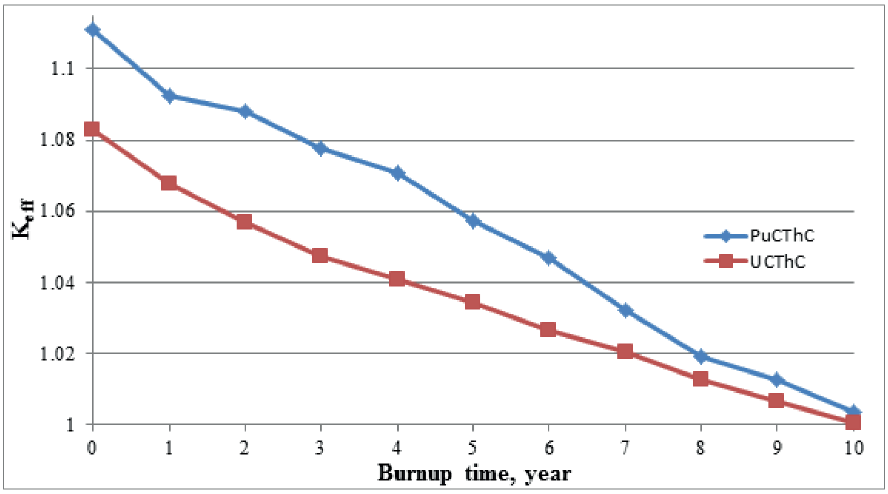

Figure 3: Dependence of the effective multiplication factor of the reactor core of a research reactor on the nuclear fuel campaign for UC-ThC и PuC-ThC fuel compositions.

To achieve the reserve of reactivity necessary to maintain a 10-year fuel campaign, the PuO_2 content in the fuel mixture is 10%. Detailed information of the composition of the fuel is presented in Table 3.

Figure 2 shows the dependence of the effective multiplication factor of the core of a research reactor on the nuclear fuel campaign for UO_2-ThO_2 and PuO_2-ThO_2 fuel compositions. It can be seen from the figure that the uranium-plutonium fuel campaign requires compensation for a smaller reactivity reserve at the beginning of the campaign at 3.5% versus 9.5% for plutonium-thorium fuel, and therefore less absorbing material.

The fuel composition PuO_2-ThO_2 has the problem of deficiency of delayed neutrons. The fraction of delayed neutrons in plutonium-thorium fuel is 0.210%, which is significantly lower compared with 0.672% in uranium load [8].

For comparison, Table 3 shows the changes in nuclear concentrations of some heavy isotopes (^{232}Th, ^{233}Pa, ^{233}U) during the nuclear fuel campaign for UO_2-ThO_2 and PuO_2-ThO_2 fuel compositions.

The possibility of using carbide fuel with the following parameters was considered in the paper: (Pu + Th)C (PuC in the mixture is 4.5%), (U + Th)C (PuC in the mixture is 15%). - Dependence of the effective multiplication factor of the core of the research reactor on the nuclear fuel campaign for UC-ThC and PuC-ThC fuel compositions is shown in Figure 3.

The most common carbide compounds are UC and PuC monocarbides. Their density is somewhat higher than that of dioxide and is ~ 14 g / cm3. Thermal conductivity is close to the thermal conductivity of metallic uranium and is ~ 15-20 kcal / (m hour ° s), i.e. ~ 10 times higher than that of UO2. The melting point is also high (~ 2450 ° C), which makes it possible to operate this fuel at temperatures up to ~ 2200 ° C [10]. But in this work, the operating temperature of the fuel is 260 ° C. The main part of the research on the application of carbide fuel in nuclear reactors was carried out for reactors with a fast spectrum. In this paper, carbide fuel is used for a thermal reactor.

4. Conclusion

The simple arrangement of the reactor, the absence of a pressure-bearing housing, the use of a cheap coolant (water), a small number of activated structural materials, the relative compactness of the plant as a whole, and the use of common industrial enrichment fuel make the research reactor concept attractive not only from a technical, but also an economic point of view. The use of fuel with enrichment below 20% allows to ensure export potential.

Calculations showed that, from the point of view of neutron-physical characteristics, the use of oxide fuel is more effective. This will reduce the amount of absorbent material to compensate for initial reactivity.

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