

USE OF THORIUM IN THERMAL-NEUTRON REACTORS: COMPUTATION MODEL AND COMPARISON OF NEUTRONIC CODES

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ABSTRACT

This research is about feasibility study for using thorium-based fuel composition in commercial nuclear power reactors. The article describes comparison of different type of software resources for carrying out neutronic computations for reactor core. To carry out neutron-physical computations the following software resources were chosen: MCU-PTR, WIMSD-5B, WIMS-ANL. Results of research show that precision software MCU-PTR (Monte Carlo method) demonstrates most accuracy results of calculations. WIMS-family software can be used only for estimated calculations because of its one-dimensional geometrical model. However, isotopic concentrations in fuel assemblies during fuel cycle are correct for all of three software. Moreover, showed software allow calculate changes of reactivity margin.

INTRODUCTION

The explored resources of thorium in the earth crust are several times higher than the reserves of uranium and this significantly increases nuclear energy's resource base in case of implementing closed nuclear fuel cycle.

30 isotopes of thorium are known as well as 3 excited metastable states of its nuclides. Only one isotope of thorium (thorium-232) has sufficiently long half-life with respect to the Earth's age, therefore, almost all of natural thorium consists of this nuclide only. Th^{232} itself is not fission by thermal neutrons, but absorption of neutron by thorium-232 leads to generation of uranium-233, which has high probability to emit neutrons as a result of fission by thermal and intermediate neutron fluxes. Therefore, it plays the same role in a nuclear reactor as U^{238} : nuclides absorbing neutrons transform into secondary nuclides, which can fission by thermal neutrons.

Thorium-232 is the best "resource" isotope compared with uranium-238 for the reactors with a thermal neutron spectrum. Uranium-233 emits more than two neutrons per capture of one primary neutron for wide range of reactors with a thermal neutron

spectrum.

Thorium dioxide has greater chemical and radiation resistance compared with uranium dioxide, as well as better thermal-physical properties (thermal conductivity, linear expansion coefficient).

Secondary nuclear fuel in thermal-neutron reactors is two isotopes of plutonium: Pu^{239} and Pu^{241} . The former is generated as a result of absorption of thermal and resonance neutrons by U^{238} nuclei, the latter is generated as a result of double radiative capture of neutrons by Pu^{239} nuclei. The scheme of this process is as follows:

Uranium isotope U^{233} is the secondary nuclear fuel in thorium thermal-neutron reactors. The scheme of this process is as follows:

U^{233} has big value of η_{eff} coefficient, which represents the number of secondary neutrons per one neutron absorbed by nuclear fuel:

When transitioning from uranium to thorium fuel cycle, production rate of long-lived minor actinides significantly decreases in a nuclear reactor. If thorium reactor operates exclusively in a U^{232} -Th fuel cycle, actinides with masses higher 237 will accumulate in negligible amounts in the reactor.

Isotope U^{232} draws special attention in thorium-based cycle. It is generated by means of $(n,2n)$ reaction taking place on Th^{232} , Pa^{233} and U^{233} isotopes. Half-life of U^{232} is 69 years. Among its daughter products are Tl^{208} – isotope with very short lifetime emitting hard gamma particles (2.6 MeV) (Belle and Berman, 1984).

Dose rates in thorium fuel will rise due to accumulation of U^{232} . This creates additional problems when dealing with spent nuclear fuel of thorium reactors, in particular, when re-cyclization of uranium takes place. However, at the same time, presence of U^{232} in spent fuel increases proliferation security of this nuclear cycle. Besides, thorium fuel cycle is more preferable with respect to utilizing weapon-grade plutonium since it does not lead to its reproduction as in case of using U-Pu fuel cycle.

The “classic” drawback of thorium fuel cycle is relatively high half-life of its intermediate product Pa^{233} (27 days), which is an order of magnitude higher than of Np^{239} (2.36 days). As a result, a significant equilibrium concentration of Pa^{233} is generated in thorium-based reactors and due to radiative capture on its nuclides, further neutron losses take place.

A protactinium effect shall surely be observed in thorium-based reactors. This effect is similar to the neptunium effect in fast-neutron reactors with uranium or uranium-plutonium fuel but is worse in terms of control. Rise of reactivity during extended shutdowns caused by fission of Pa^{233} and

its transformation into U^{233} should be taken into consideration when designing projects of thorium-based reactors.

Works on exploring the possibilities of using thorium in nuclear fuel cycle are based on either high reserves of thorium (India), or desire to reduce the consumption of nature uranium (Norway), or nuclear energy technology capable of taking advantage of thorium fuel cycle (Canada, Russia).

RESULTS

Computation Model of the vver-1000 Reactor Cell

Computation model is an elementary cell of the VVER-1000 reactor with infinite height, consisting of a fuel element surrounded by water coolant. During the computation, real hexagon cell is replaced by equivalent cylindrical cell with cross-section of a real one (Fig. 1-4).

Fuel element’s core (zone 2) with a radius of 0.39 cm has inner hole with a diameter of 0.07 cm (zone 1). Zone 3 represents fuel element’s cladding; zone 4 represents water coolant (and moderator).

Fuel element’s cladding of the VVER-1000 reactor is made from zirconium alloy with the outer diameter of 0.91 cm and thickness of 0.65 cm. Fuel pellet made from uranium dioxide has the outer diameter of 0.78 cm and axial hole with the diameter of 0.14 cm. Placement step of fuel elements is 1.275 cm.

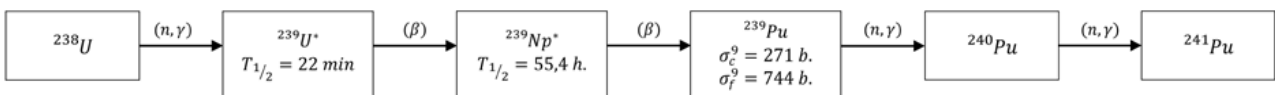


Fig. 1 Chain of generation of new nuclei from uranium-238.

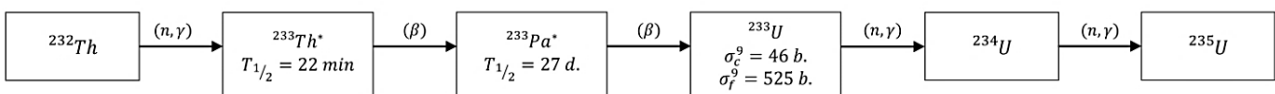


Fig. 2 Chain of generation of new nuclei from thorium-232.

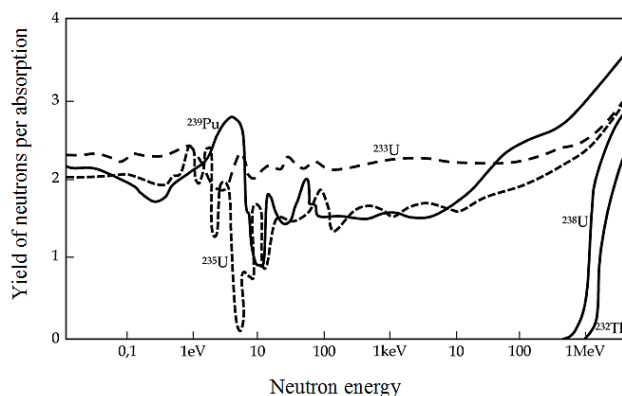


Fig. 3 η_{eff} for different isotopes.

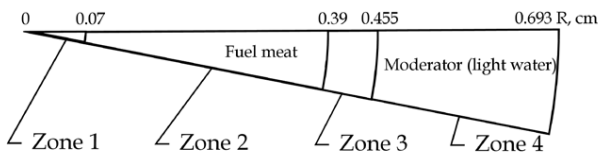


Fig. 4 Computation model.

Material composition of the basic description of fuel elements is represented by uranium dioxide with density of 10.5 g/cm³ and 4.5 % U²³⁵ enrichment. Cladding is made from zirconium alloy with 1 % niobium. Water density corresponds to pressure of 16 MPa and temperature of 300°C.

Comparison of Software for carrying out Computation

Major aspect of carrying out neutron-physical computations of thorium-based fuel assemblies is difference of values of interaction cross-sections in evaluated nuclear databases; therefore, it is required to carry out comparative analysis of different software resources suitable for the computation, which use different databases (Chadwick *et al.*, 2006).

To carry out neutron-physical computations the following software resources were chosen:

- One-dimensional cell software WIMS-ANL with 69-group ANL library obtained on the basis of ENDF/B-VI evaluated nuclear data (Deen *et al.*, 2004);
- One-dimensional cell software WIMSD-5B with the library based on ENDF/B-VI.7 evaluated nuclear data (Halsall, 1996);
- Three-dimensional precision software MCU-PTR with MDBPT50 library based on ENDF/B-VII.0 evaluated nuclear data (Alekseev and Gomin, 2011).

To determine special features of the computation in different software, a model of the VVER fuel element with UO₂ based fuel with 20 % enrichment was chosen.

Fig. 5 shows reactivity margin vs. a reactor operating cycle obtained in different software.

It can be noted that all three software resources show results of high convergence when estimating length of reactor operating cycle. Differences between the results obtained in MCU-PTR and WIMS-ANL does not vary more than 1.5%; in MCU-PTR and WIMSD-5B – no more than 2%.

During computation of thorium-based fuel compositions besides determining the length of reactor operating cycle, major aspect is the correct computation of concentration of the nuclides

involved in nuclear chains of reproducing materials transforming into fissionable materials.

Fig. 6 and 7 show concentration (obtained from different software) of the following nuclides during the operating cycle: U²³⁵, U²³⁸, Np²³⁹, Pu²³⁹.

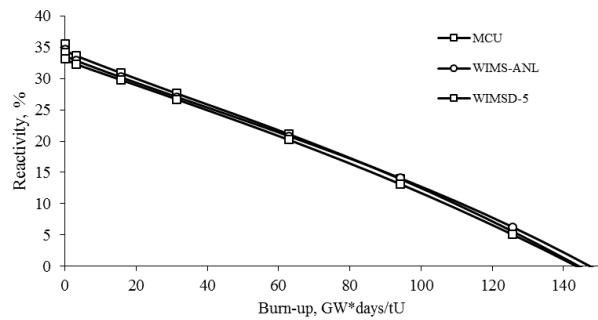


Fig. 5 Reactivity margin during a reactor operating cycle

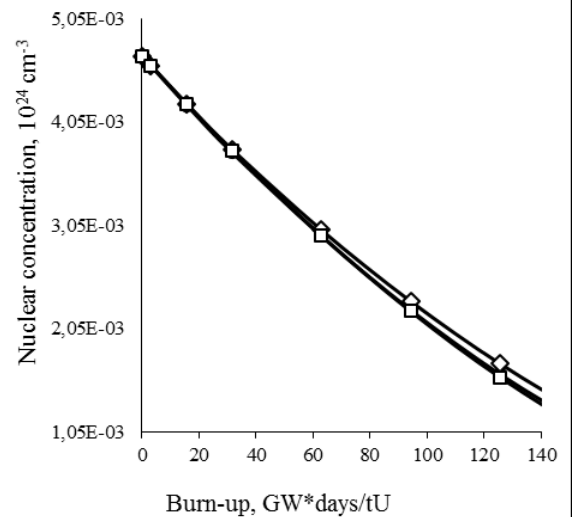


Fig. 6 Nuclear concentration of U²³⁵ (left) and U²³⁸ (right) during reactor operating cycle.

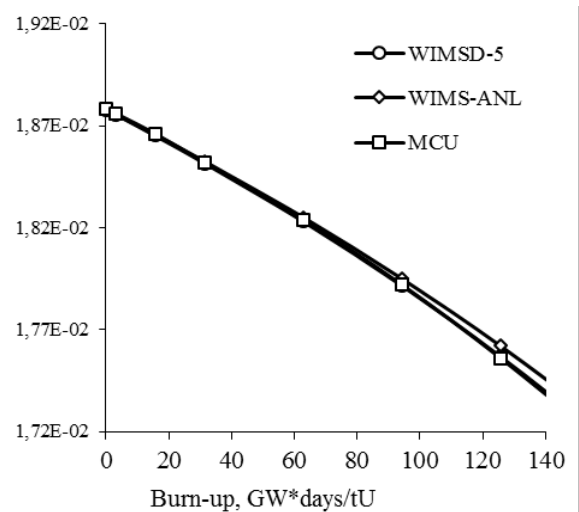


Fig. 7 Nuclear concentration of Np²³⁹ (left) and Pu²³⁹ (right) during reactor operating cycle.

It can be noted that all three software quite precisely determine concentration of elements of the fuel composition. However, it is observed that the results obtained by means of WIMSD5B software significantly deviate from the results obtained by means of MCU-PTR software. At the value of fuel burn-up of 100 GW*days/tU and higher, WIMSD-5B software overstates the concentration of Pu-239 by 20-25%.

CONCLUSION

Main problem of exploring research of using thorium in fuel cycles is accuracy of library based on evaluated nuclear data. For example, error of microscopic cross-section for some reactions can reach about 50 %.

Our calculations show that, more suitable software for neutronic calculations of thorium-based fuel cycles is the three-dimensional precision software MCU-PTR with MDBPT50 library based on ENDF/B-VII.0 evaluated nuclear data. High precision results also shown by one-dimensional cell software WIMS-ANL with 69-group ANL library obtained on the basis of ENDF/B-VI evaluated nuclear data. So, neutron-physical computations were carried out by means of one-dimensional cell WIMS-ANL software

with 69-group ANL library. Specifying computations were carried out using MCU-PTR precision software.

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