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Variants of the perspective closed fuel cycle, based on Regenerated Mixture – Technology, combining use of thermal and fast reactors

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ABSTRACT

In the traditional closed fuel cycle, based on REMIX-technology (**RE**generated **MIX**ture of U and Pu oxides) the fuel composition is produced on the basis of a uranium and plutonium mixture from depleted Light Water Reactor (LWR) fuel and additional natural uranium. In this case, there is some saving in the amount of natural uranium used. Here variants are considered of the perspective closed fuel cycle in which fissile feed materials for fuel manufacture is produced in the blankets of fast breeder reactors. The fissile material is ^{233}U or Pu. The raw material is depleted uranium from the stocks of enrichment factories, or thorium. Natural uranium is not used in this case. The minimum feed material required for the REMIX technology in a closed fuel cycle was determined through calculations of different types of fissile and raw materials, with different cycle lengths and fuel-water ratios.

1. Introduction

Nuclear energy in Russia, up to 2030 years will be based largely on WWER reactor technology. Meanwhile, more time, effort and money have been invested in the development of LWRs than for any other reactor types in the world. The WWER reactors to be built in Russia and abroad up to 2030, during their 60 years of exploitation, will in the main use the inventory of cheap uranium in Russia (~650,000 tons), working in an open fuel cycle during their 60 years of exploitation. The basic strategy of Russian Atomic Energy is the propagation of the closed fuel cycle with ultimately the use of ^{238}U and ^{232}Th raw materials on the basis of fast breeder and thermal reactors, as well as the solution of the spent nuclear fuel accumulation problem. Previous work (Ponomarev-Stepnoi et al., 2005; Pavlovichev et al., 2006, 2008; Fedorov et al., 2005; Alekseev et al., 2012a,b; Zilberman et al., 2013) has suggested improved fuel usage in existing WWER-1000 type reactors, including the use of MOX-fuel and REMIX-fuel technologies.

Here, variants of closed fuel cycles are considered, for fast breeder and thermal reactors, without the use of natural uranium. The fast breeder reactors which produce excess of fissile materials (^{233}U and Pu) in fertile (Th or depleted U) loaded blankets, and the thermal reactors which use these fissile materials are the main components of these closed fuel cycles. These fissile materials are used as feed materials in the fuel fabrication process. The raw material is depleted uranium from the stocks of enrichment factories, or thorium. The fast breeder reactor BN-1200 with MOX-fuel and a breeding ratio (BR) of ~1.21 was taken as prototype in that work for the fissile material isotopic condition evaluation in the blanket region (Poplavskii et al., 2010). The main feature of these fuel compositions is that there is no need to use natural uranium.

The types of fuel compositions for thermal WWER-1000 type reactors in the system are:

- Type 1: UO_2 (depleted uranium)-PuO_2 (Pu from the blankets of fast breeder reactors);
- Type 2: UO_2 (depleted uranium)-$^{233}UO_2$ (^{233}U from the blankets of fast breeder reactors);
- Type 3: ThO_2–PuO_2 (Pu from the blankets of fast breeder reactors);
- Type 4: ThO_2–$^{233}UO_2$ (^{233}U from the blankets of fast breeder reactors).

In this system it is necessary to find the proper characteristics of the WWER-1000 core cycle with a minimum annual input of fissile material (^{233}U or Pu) produced in the blankets of the BN-1200 reactor.

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A parametric investigation was conducted in this work. During this the following parameters were varied relative to a 4-year reloading cycle for the standard WWER-1000 assemblies with a water-fuel ratio of 2.0 (*standard fuel cycle*):

- the water-fuel ratio (varied from 1.5 to 2.5) in WWER assemblies (i.e. extended and slightly tighter lattices);
- fuel cycles with 3–5 reloadings, with the length of the fuel micro-campaign – 300 effective days (therefore leading to 900, 1200 and 1500 effective days fuel campaigns).

The process of closing the fuel cycle with the usage of REMIX-technology was investigated for different combinations of these variables. All calculations in this paper were carried out using the WWER-1000 fuel assembly model. Neutron-physical calculations were realized using the code – CONSUL (Chibinyaev et al., 2007), which was developed in the National Research Center "Kurchatov Institute".

2. A perspective closed fuel cycle based on REMIX-technology for the WWER reactors with the use of depleted uranium

Fuel compositions 1 and 2 based on depleted uranium row material use in the WWER reactor, working in a closed fuel cycle based on REMIX-technology (**RE**generated **MIX**ture of U and Pu oxides) are described in this Section of the investigation. For the fabrication of REMIX-composition fuel (after zero recycle), the following components are used: uranium–plutonium regenerate (undivided mixture of uranium and plutonium from spent nuclear fuel), a small amount of depleted uranium and feed material (Pu or ^{233}U) from blankets of fast breeder reactors. Uranium-plutonium regenerate was separated from the spent nuclear fuel for base types 1 or 2. In this case we take all of the uranium–plutonium regenerate from the spent fuel. During reprocessing the accumulated fission products (FP) and minor actinides are separated. The total duration of spent nuclear fuel aging in the intermediate storage, reprocessing of spent nuclear fuel and the fabrication processes is 5 years. The mass difference of fresh and burned fuel was completed with feed material from blankets of fast breeder reactors. For reactor systems with different variable parameters (for different values of the cycle length and water-fuel ratio) at each step of the recycle, a certain amount of Pu or ^{233}U was selected to provide 300 effective days of the fuel micro-campaign. Computational studies for 5 recycles (including zero recycle) were performed in this work.

The following plutonium composition is produced in the uranium blankets of the BN-1200 fast reactor: ^{238}Pu: 0.06%, ^{239}Pu: 96.19%, ^{240}Pu: 3.64%, ^{241}Pu: 0.10%, ^{242}Pu: 0.01%.

The following uranium (^{233}U) composition is produced in the thorium blankets (according to the preliminary calculations, obtained using a PC CONSUL (Poplavskii et al., 2010; Chibinyaev et al., 2007)):

^{232}U: 1.5%, ^{233}U: 97.5%, ^{234}U: 1.0%.

The content of ^{235}U in depleted uranium is 0.2%.

It is important to mention that the amount of ^{233}U that can be produced in a fast breeder reactor blanket from thorium is lesser than the amount of Pu produced from depleted uranium. Pu surplus in BN-1200 with BR = 1.21 (Poplavskii et al., 2010) is about 250 kg a^{-1}, for Th blankets this characteristic is approximately 195 kg a^{-1}.

The main characteristics of fuel rods for a WWER-1000 assembly are presented in Table 1.

In these parametric studies the minimum feed material in the REMIX-technology for a closed fuel cycle was determined.

Table 2 shows the calculated amount of Pu in the fuel rod, in gram per year (reduced to one year: the total weight divided by the amount of years), which is required for the implementation of 3, 4 and 5-year reloadings with water-fuel ratio 1.50, 2.00, 2.50. Table 3 shows the calculated amount of ^{233}U in the fuel rod, in gram per year (reduced to one year: total weight divided by the amount of years), which is required for the implementation of 3, 4, 5-year reloadings with water-fuel ratio 1.50, 2.00, 2.50. The information is reported for zero, 1st and 4th recycle with REMIX-technology usage.

Table 1
Mass density and basic geometric characteristics of a WWER-1000 assembly.

Parameter	Value
Mass density oxide fuel (g cm^{-3})	10.38
The radius of the fuel pellet (cm)	0.3775
External/internal radius of the cladding (cm)	0.386/0.4557
Fuel height (cm)	353
Mass of the heavy metal in the fuel rod (g)	1388.39

The investigation shows that the main isotopic composition of fresh fuel is stabilized to the 4-th recycle time. The exception is for isotopes ^{234}U and ^{238}Pu, for which concentrations continue to increase from recycle to recycle. It should be mentioned, that the change in water-uranium ratio leads to structural changes in the fuel assemblies of the WWER-1000 reactor and an increase in the hydraulic resistance of the core which require further investigation. The annual fissile material use decreases if ^{233}U from blankets of fast breeder reactors is used.

According to Table 2, for zero recycle, the larger number of reloadings and higher water-fuel ratio leads to a decrease in feed material use. The first recycle gives 20% saving of feed fissile material in the *standard fuel cycle* (central point in the Table) which rises to 33% in the 4-th recycle. For the 4-th recycle the larger number of reloadings and tight lattices yield the minimum in feed material use. The number of BN-1200 reactors that can feed one WWER-1000 reactor with their surplus Pu is 3. Implementation of the REMIX-technology for WWER-1000 closed fuel cycle reduces this number to 2.

According to Table 3, for zero recycle, the larger number of reloadings and higher water-fuel ratio leads to decreasing feed material use. There is no difference between 2 and 2.5 water-fuel ratio. The first recycle gives 16% saving in feed fissile material in the *standard fuel cycle*, which rises to 25% in the 4-th recycle. For the 4-th recycle the lower number of reloadings and tight lattices give the minimum feed material use. The lower amount of ^{233}U feed material in comparison with Pu does not reduce the number BN-

Table 2
Annual required amount (in grams per year for one WWER-1000 fuel rod) of Pu from BN-1200 blankets for uranium fuel and for the implementation of 3, 4, 5-year reloadings with water-fuel ratio 1.50, 2.00, 2.50 (zero, 1st, 4th recycle).

0 Recycle			
Water/fuel ratio (–)	1.5	2.0	2.5
Reloading time (a)	Annual plutonium requirement (g a^{-1})		
3	22.7	17.6	16.0
4	20.5	16.3	14.8
5	19.0	15.4	14.0
1st Recycle			
Water/fuel ratio (–)	1.5	2.0	2.5
Reloading time (a)	Annual plutonium requirement (g a^{-1})		
3	22.7	13.0	12.5
4	20.5	13.0	12.6
5	19.0	12.7	12.6
4th Recycle			
Water/fuel ratio (–)	1.5	2.0	2.5
Reloading time (a)	Annual plutonium requirement (g a^{-1})		
3	10.3	10.9	11.2
4	10.2	10.9	11.3
5	10.0	11.0	11.4