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Research Article

Multiple usage of thorium-based fuel in a VVER-1000 reactor*

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Abstract

This paper considers the use of unconventional fuel in nuclear power reactors, using the example of a VVER-type unit, in order to find out the possibility of saving natural fissile uranium nuclei. Saving fissile uranium is one of the important tasks, the solution of which will give time for the development of a two-component nuclear power industry that will have no problems with fuel resources. However, at present, the reserves of cheap uranium can provide the existing level of global nuclear energy for only 80–100 years.

The main components of this proposed fuel are ^{232}Th and fissile isotopes of uranium: ^{235}U (loaded) and ^{233}U (produced from thorium). All the uranium isotopes and added ^{235}U nuclei at the beginning of the campaign account for about 6% of the number of thorium nuclei and uranium isotopes. The abbreviated name of this fuel is TORUR-5.

To keep fissionable nuclei in the fuel cycle after the spent fuel is unloaded, it is envisaged that all the heavy nuclei will be returned back to the reactor after they have been cleaned from fission fragments, i.e., the fuel cycle will be closed. At the same time, the principle of annual movement of fuel assemblies (as they burn up) is the same as in the existing VVER-1000 reactors.

Using the Serpent software, a reactor model was built, the composition and dimensions of which were close to the parameters of the VVER-1000 serial unit. The main results of calculations were the quantitative compositions of isotopes annually loaded into the reactor as well as the amounts of ^{235}U and thorium added also annually. The analysis of the obtained results allowed us to make the following conclusions.

The annual reloading of ^{235}U during the computation period is required almost at a constant level and, in comparison with uranium fuel, is about half as much. This is feasible for the following reasons. Part of the fissions of ^{235}U is replaced by the fission of ^{233}U produced from ^{232}Th. In addition, fissionable nuclei are kept in the closed Th-U fuel cycle. This is the first "advantage" of the proposed fuel. TORUR-5 requires uranium enriched to at least 90%, the cost of which is several times higher than that of 3–5% enriched uranium.

But since much less highly enriched uranium is required, the cost of fuel for a TORUR-5-fueled VVER-1000 reactor is significantly lower. This is the second "advantage" of the proposed fuel.

The negative characteristic of TORUR-5, which requires further investigation, is that, after the initial loading, several uranium isotopes appear in the returned fuel, the total radioactivity of which, according to estimates, exceeds the radioactivity of traditional 3–5% enriched uranium fuel by several thousand times. At the same time, the radioactivity of discharged spent conventional fuel exceeds the radioactivity of fresh fuel by millions of times, and this problem has been solved at NPPs both organizationally and technically. Therefore, it will be necessary to develop a technology for loading TORUR-5, taking into account the estimated radioactivity.

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Keywords

VVER-1000, thorium, uranium-thorium fuel cycle, multiple use of fuel, saving natural resources

Research objective

As is known, the sources of natural uranium are limited (NEA 2020), especially those of fissile isotopes (there are only 0.72% of them in natural uranium), without which it is impossible to build nuclear power based on thermal neutron reactors with uranium-plutonium fuel. Today, the electrical power of the nuclear power industry on our planet is about 400 GW (IAEA 2022), and the thermal power, taking into account the fact that the average thermodynamic efficiency is 32%, is 1250 GW. Thermal neutron power reactors operate in an open fuel cycle using uranium dioxide containing up to 5% fissile ^{235}U (Bat et al. 1989).

Let us use data on the fuel cycle of VVER-1000 reactors, the most common type of nuclear power plant reactors, to estimate the annual consumption of uranium in the nuclear power industry, assuming (not without reason) that the consumption of uranium in the end in an open fuel cycle with uranium fuel does not depend at a first approximation on the enrichment of fresh fuel. It is known, for example, that the thermal power of the VVER-1000 reactor is 3.2 GW with fuel loading into the core of 80 tons (Bat et al. 1989). Consequently, with a three-year fuel cycle, the annual addition of fuel during reloading is equal to 26.7 tons of uranium enriched up to 4.4% (Ovchinnikov and Semenov 1988). For enrichment, it is required to use natural uranium, the consumption of which (with a content of 0.2% ^{235}U in depleted uranium) is 7.08 tons of natural uranium, enriched to 4.4%, per ton (Lebedev 2005). Thus, about 74,000 tons of natural uranium is required annually for the entire power industry.

Table 1 shows the relationship between the cost and reserves of uranium: the cost of uranium is dependent on its reserves, i.e., the higher the cost, the more natural reserves (NEA 2020).

Table 1. Estimated Uranium Reserves (in tons)

	Uranium price, $/kg			
	< 40	< 80	< 130	< 250
Uranium mass, t	1,080,500	2,007,600	6,147,800	8,070,400

This means that if there is a willingness to pay $260/kg for uranium, then the nuclear power industry will be provided with uranium resources at the current level for 109 years. And with a limit of $130/kg, the resources will last only 83 years.

The deployment of a large-scale power industry with fast reactors will take several decades, when cheap natural resources of uranium will be depleted. Therefore, issues related to the economy of fissile ^{235}U nuclei may become relevant. Interest in various fuel compositions for thermal neutron reactors with fuel cycle closure (i.e., return of heavy nuclei to the reactor after their chemical separation from spent fuel), including the introduction of thorium into the fuel, began to appear more than 30 years ago, for example, the possibility of accumulating ^{233}U in VVER reactors was considered in Yurova et al. 1978.

Saving uranium is possible in the power industry with thermal neutron reactors operating at supercritical parameters. Currently, this technology is being actively studied in order to solve the problems presented, for example, in Kirillov and Bogoslovskaya 2018. At the same time, there is no need to close the fuel cycle in the power industry with thermal reactors. Other methods are associated with a change in the composition of the fuel and the mandatory closure of the fuel cycle.

First of all, we should note the French research on replacing some of the fresh uranium fuel in operating reactors with uranium, plutonium and a complex combination of uranium, plutonium and thorium separated from spent nuclear fuel (SNF). The results of French researchers' experiments with thorium-plutonium MOX fuel have shown that it has some advantages over U-Pu MOX fuel (Sylvain et al. 2007).

Russian researchers have confirmed the possibility of accumulating ^{233}U in VVER-type reactors. However, they focused on ways to minimize the accumulation of ^{232}U but not at the stage of switching to Th-U fuel (Yurova et al. 1978). Since ordinary water has a high neutron absorption, light water reactors will not be able to demonstrate the full potential of the thorium cycle. Thus, in Marshalkin 2019, a method was considered for operating a nuclear reactor in a closed thorium fuel cycle, which includes the initial loading of the reactor core with oxide uranium-thorium fuel, using the coolant diluted with heavy water. Such a scheme, when heavy water is diluted with ordinary water up to 80%, makes it possible to achieve reproduction of fissile ^{233}U. However, it should be noted that heavy water is currently not provided for in the operation of commercial VVER-1000 reactors. Therefore, the question concerning the possibility of introducing a uranium-thorium cycle for currently operating VVER-1000 reactors in order to save natural uranium sources remains open.

In the late 1990s, the possibility of using thorium as applied to existing pressurized reactors was investigated in Ponomarev-Stepnoy et al. 1998. The seed scheme in this modification of VVER-T was used for long-term (about six years) campaigns. However, recycling of fuel was not envisaged. More recent data obtained by Shamanin et al. 2016 indicate that, to use an ultralong campaign, the reactor must operate on epithermal neutrons. However, this paper raises the question of introducing thorium for existing and successfully operating VVER-1000 reactors.

There are also studies of the potential of the thorium cycle carried out by foreign scientists Frybort 2014, Hassan et al. 2020, Reda et al. 2021, where the advantages of fuel containing thorium and the possibility of its use in thermal reactors, including VVER-type reactors, have been shown. Among the earlier experiments, it is worth mentioning the Indian Point-1 nuclear power plant, which operated from 1962 to 1980, with a capacity of 265 MW. In the core of the Indian Point-1 NPP, a solid solution of uranium-thorium fuel was used as fuel. The project showed that the extraction of ^{233}U turned out to be an "economic disaster" (Alvarez 2014). Moreover, according to the materials of the IAEA Thorium-Based Nuclear Fuel: Current Status and Perspectives 1987 (IAEA 1987), in the 1960s at the Elk River NPP with a boiling water reactor (BWR) with a capacity of 22 MW, uranium-thorium oxide fuel was also used as nuclear fuel. This fuel was reprocessed, but the fuel reprocessing facility proved to be technically imperfect.

This paper considers one of the possible ways to reduce the consumption of fissile uranium nuclei in operating pressurized water reactors (PWRs) of NPPs. The idea is to switch thermal reactors to a new fuel, a mixture of ^{235}U dioxide and thorium dioxide (abbreviated as TORUR-5), as well as to close the fuel cycle.

For the manufacture of fresh fuel from SNF, heavy nuclei are isolated with the addition of ^{235}U and thorium to restore the reactivity margin. Closing the fuel cycle for the return of uranium and thorium to the reactor after they are cleaned from fission fragments reduces the amount of necessary additional loading of ^{235}U.

In the calculations performed, the time dependence of the isotopic composition of the unloaded and, consequently, loaded fuel is determined. This is important because the isotopic composition of uranium changes not only due to the formation of fissile ^{233}U nuclei and the remnant of unburned ^{235}U nuclei, but also due to the formation of new neutron absorbers, i.e., nuclei such as ^{234}U and ^{236}U.

The accumulation of the latter increases the required additional loading of ^{235}U nuclei and thus reduces the gain from using the proposed fuel. Therefore, it is necessary to determine the most effective number of refuelings with the recovery of uranium and thorium from spent fuel.

It is also necessary to determine the amount of its 232nd isotope accumulated in uranium. The accumulation of this isotope will have little effect on the economy of ^{235}U nuclei, since in a thermal reactor the ratio of the radiation capture cross sections to the fission cross sections for this isotope is close to unity. However, ^{232}U has a short half-life, which can affect the radioactivity and power release of recovered uranium from SNF. This will require additional constructive and organizational measures at NPPs. Finally, it is necessary to determine how the enrichment of uranium in the addition of fuel will affect the parameters of such a fuel cycle.

Calculation model

For the calculations, we used the Serpent software package based on the Monte Carlo method (SERPENT – MCRPBCC 2022) and the mode of independent calculation of fuel burnup associated with the calculated data. We also used nuclear data from the JEFF-3.1.1 library. The calculations were carried out at constant temperatures of the reactor operating only at the nominal power level (in the hot state).

Table 2. Core Geometry

Parameter	Value
Thermal power, MW	3210
Core height in working condition, mm	3550
Core specific power, MW/m^2	115
Number of fuel assemblies, pcs.	163
Number of fuel elements in fuel assemblies, pcs.	312
Fuel assembly width across flats/pitch, mm	234/236
Fuel element outer diameter/pitch, mm	9.1 × 0.65/12.75
UO_2 fuel loading in the core, t	80.098
Average fuel loading in fuel assemblies, kg	491.4
Number of guide channels, pcs.	18
Guide channel diameter, mm.	12.6 × 0.85
Fuel pellet diameter, mm	7.57
Fuel pellet hole diameter, mm	1.4
Operational life in an equilibrium fuel cycle, eff. days	350
Average enrichment of loaded fuel assemblies, %	4.2
Number of reloaded fuel assemblies, pcs.	54

The task of the calculation was to compare the consumption of ^{235}U with traditional fuel and with TORUR-5 fuel. The model was based on a serial core of the VVER-1000 reactor (Kolobashkin et al. 1989; Andrushechko et al. 2010) from which detailed data were taken on the geometry and composition of fuel elements and fuel assemblies, as well as on the composition and mass of the annual addition of fuel and the mass of fuel in the core. These data are necessary for preparing the calculation model and for determining the load of TORUR-5 fuel and the consumption of ^{235}U. However, the "consumption" of ^{235}U does not take into account that part of it that could potentially participate in a closed fuel cycle after the end of the fuel campaign in the traditional fuel cycle. The dimensions and materials for the calculation were borrowed from (Andrushechko et al. 2010): they are given in . 2.

Based on the data in the table, we can determine that the annual consumption of ^{235}U in the existing fuel cycle is 982 kg.

The fuel assembly of the VVER-1000 reactor has 312 fuel elements, 18 holes for absorbers, and a central tube (Fig. 1). This design was taken as a basis and remained unchanged at each stage of calculations. One hundred and sixty-three such fuel assemblies form the core geometry shown in Fig. 2.

Fig. 2 shows a horizontal cross section of the core, indicating the placement of the fuel assemblies immediately after loading fresh fuel into the reactor. The reactor consists of the following three sections:

Section 1 containing "fresh" fuel (with zero iteration, traditional fuel is used, i.e., ^{238}U with 4.2% enrichment in ^{235}U; thorium and ^{235}U are in subsequent iterations);

Section 2 containing assemblies that have worked for a year (350 days), with fission products and a modified composition of heavy nuclei; and

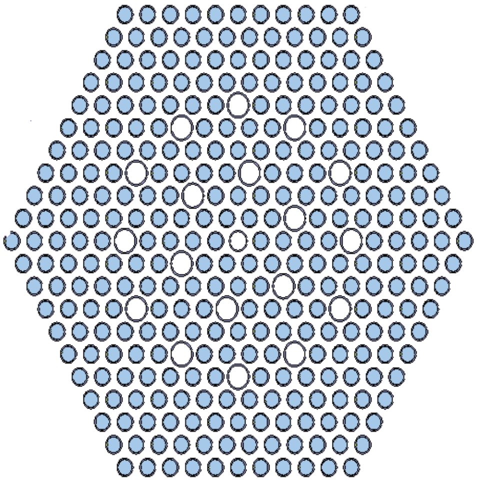

Figure 1. Horizontal cross section of the fuel assembly of the VVER-1000 reactor.

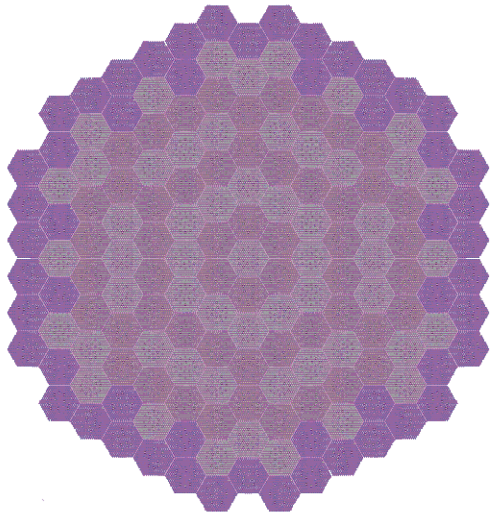

Figure 2. Core consisting of three sections with different burnups. Purple color indicates "fresh" fuel assemblies (Section 1), gray color indicates fuel assemblies after one year of reactor operation (Section 2), pink color indicates fuel assemblies after two years of reactor operation (Section 3).

Section 3 containing assemblies that have been in operation for two years (700 days), with fission products and a modified composition of heavy nuclei.

One iteration involves the calculation of the reactor campaign (350 days), i.e., determination of changes in the compositions of fuel sections (1, 2 and 3), reactivity and burnup during a given period of time.

Every 350 days, we have new section compositions at the outlet, and the reactor is refueled as follows. "Fresher" fuel is moved to the fuel assemblies that have been in operation for a year, and the latter assemblies are moved to replace the ones that have been in operation for two years. The fuel assembly is returned to the place of "fresh" fuel after three years of operation of the reactor, taking into account chemical purification from fission products and the addition of ^{235}U and ^{232}Th nuclei so that the sum of heavy nuclei does not change and the reactivity at the end of the campaign differs from zero by less than one fraction of delayed neutrons for ^{235}U. The iterative process continues until the addition of fuel composition becomes unchanged. As a result, the content of ^{235}U in the resulting fuel will be compared with the initial one – for the zero iteration with traditional fuel, from which it will be possible to draw conclusions about saving natural uranium. The irradiation conditions (normalization for power, temperature, and geometry) are taken unchanged, i.e., only the fuel composition changes. The density of thorium oxide, equal to 9.87 g/cm^3, was taken from the handbook "Chemist's Handbook. Basic Properties of Inorganic and Organic Compounds" 1963 (Nikolskiy and Rabinovich 1963).

Calculation results

The main results are shown in Table 3. Each column of the table, called an iteration, shows the composition of the loaded fuel in one third of the reactor, in the same core cells (see Fig. 2).

The composition of heavy nuclei is given in units of "10^{24} nuclei/cm^3". Recall that the data on the loaded fuel, from which additional loadings of thorium and ^{235}U are subtracted, represent the composition of heavy nuclei after the extraction of fission fragments. Taking into account the data in Table 2, we can find the relationship between the concentrations and the mass of unloaded and loaded fuel, i.e., consumption of ^{235}U. The transition coefficient from the concentration of ^{235}U to its mass was $1.014 \cdot 10^{-18}$ kg.cm^3/number of nuclei.

In the first three iterations, the burnt-up fuel with uranium, plutonium and minor actinides is sent to SNF storage facilities according to the standard scheme and is replaced by TORUR-5 fuel (thorium with the addition of ^{235}U). The load for the fourth and subsequent iterations is formed from uranium and thorium separated from SNF, purified from fission fragments and with the addition of ^{235}U and thorium, which is indicated in the penultimate rows of the table to compensate for their burnup. The table is built on the assumption that reprocessing SNF and manufacturing fresh fuel elements and fuel assemblies are carried out instantly. It is obvious that the annual consumption of ^{235}U is determined by the amounts shown in the penultimate rows of the tables. The average value of the annual consumption is $(5.76 \pm 0.28) \cdot 10^{20}$ nuclei/cm^3 starting from the fourth iteration (according to the data of Table 3). Using the found concentration and the total volume of fuel assemblies being reloaded (54 pcs), which remains unchanged during all the iterations, we conclude that the annual mass consumption of ^{235}U in this case will be 584 kg.

Previously, in the Calculation Model Section, the number of reloaded fuel elements, the total mass of fuel loaded into the core and the average enrichment of loaded fuel assemblies were given, which makes it possible to find the annual loading of ^{235}U into the core. The annual consumption of ^{235}U for the traditional campaign turned out to be 982 kg/yr.

Table 3. Composition of some nuclei of loaded fuel in 10^{24} nuclei/cm^3

Parameter	0	1	2	3	4	5	6	7	8	9	10	11
^{232}Th	0.02114	0.02114	0.02114	0.02095	0.02096	0.02095	0.02072	0.02071	0.02074	0.02057	0.02057	0.02058
^{232}U	–	–	–	1.45E-6	1.43E-6	1.41E-6	2.81E-6	2.80E-6	2.79E-6	3.57E-6	3.57E-6	3.56E-6
^{233}U	–	–	–	3.13E-4	3.12E-4	3.11E-4	3.61E-4	3.62E-4	3.63E-4	3.75E-4	3.76E-4	3.76E-4
^{234}U	–	–	–	5.19E-5	5.18E-5	5.08E-5	1.03E-4	1.02E-4	1.02E-4	1.37E-4	1.37E-4	1.36E-4
^{235}U	0.001127	0.001127	0.001127	7.43E-4	7.41E-4	7.46E-4	7.69E-4	7.80E-4	7.51E-4	7.70E-4	7.73E-4	7.67E-4
^{236}U	–	–	–	1.53E-4	1.53E-4	1.52E-4	2.29E-4	2.29E-4	2.29E-4	3.00E-4	3.01E-4	2.98E-4
ρ (init.)	0.1206	0.1132	0.1125	0.1110	0.1111	0.1101	0.1085	0.1104	0.1097	0.1052	0.1041	0.1038
ρ (fin.)	–0.0019	–0.0042	0.0008	0.0017	–0.0004	–0.0031	–0.0005	0.0039	0.0058	0.0048	0.0048	0.0053
Δρ	0.1225	0.1174	0.1117	0.1093	0.1115	0.1132	0.1090	0.1065	0.1039	0.1004	0.0993	0.0985
^{235}U*	–	–	–	+5.4E-4	+5.4E-4	+5.4E-4	+6.1E-4	+6.2E-4	+5.9E-4	+5.8E-4	+5.8E-4	+5.8E-4
^{232}Th*	–	–	–	+6.14E-4	+6.16E-4	+6.03E-4	+5.4E-4	+5.2E-4	+5.6E-4	+5.9E-4	+6.01E-4	+5.8E-4

* = the number of nuclei added to these isotopes for the current iteration.

Thus, the annual gain in ^{235}U consumption in the case of TORUR-5 fuel is 398 kg, i.e., the reduction in the consumption of ^{235}U is 1.68 times.

This paper does not provide a detailed analysis of the economic gain (loss) in replacing uranium fuel with TORUR-5 and switching from the traditional open fuel cycle scheme to the proposed one. We will restrict ourselves to estimates of the following important characteristics that affect economic indicators. The first of them is the cost of annually additionally loaded fuel.

Let us estimate the change in the fuel cost, taking into account the required amount of natural uranium, its conversion into uranium hexafluoride, enrichment work and reverse conversion of depleted and enriched uranium into uranium dioxide.

We define the relative cost for highly enriched uranium (95% content of ^{235}U) and low enriched uranium (4.4%), which is used in the annual addition of fuel of VVER-1000 reactors, and denote it as P_{uran} (95%/4.4%). The cost of 1 kg of natural uranium in the form of dioxide will be denoted as P_{uran}, which includes the costs of converting the dioxide into uranium hexafluoride and, after enrichment, the conversion of uranium hexafluoride into dioxide. Let us designate the cost of one separation work unit (SWU) for one kg of uranium as P_{SWU}. The ratio of the costs of uranium of different enrichment is determined using the cost of natural uranium, the conversion of dioxide into uranium hexafluoride and reverse procedure, and the cost of a SWU, i.e., “P_{SWU}”. Taking into account the above remarks, the desired ratio of the costs of uranium of different enrichment can be written using the formula:

$$P_{uran}\left(\frac{95\%}{4{,}4\%}\right) = \frac{N_{SWU}\,(95\%)\cdot C\cdot N_{uran}(95\%)}{N_{SWU}\,(4{,}4\%)\cdot C\cdot N_{uran}(4{,}4\%)} \quad (1)$$

where $C = P_{uran}/P_{SWU}$; N_{SWU} is the number of SWU; N_{uran} is the amount of uranium (in kilograms).

We should add the costs of extracting fission fragments from spent nuclear fuel to the cost of highly enriched uranium. It will take about \$20/kg to purify uranium from fission fragments, i.e., about half a million dollars.

Using the data for N_{SWU} and P_{uran} from Lebedev 2005, we find the P_{uran} value (95%/4.4%) equal to 27.2 at C = 1. This value was obtained under the assumption that the cost of natural uranium is about \$60/kg, the cost of conversion of UO_2 to UF_6 is about \$10/kg and the cost of SWU is \$100/kg. The annual additional loading in the existing open fuel cycle is 26.5 tons, and the loading of highly enriched uranium in the proposed fuel cycle is 584 kg, i.e., 45.4 times smaller. Consequently, the cost of loaded uranium in the proposed version is 1.67 times less than that of additionally loaded uranium in the case of a traditional fuel cycle.

The second component may be related to the radioactivity of the additionally loaded TORUR-5 fuel. In VVER-1000 reactors, fresh fuel has a radioactivity of about $2\cdot10^{10}$ Bq/t. In the open fuel cycle, the radioactivity of the TORUR-5 fuel is approximately half as low, but when the fuel cycle is closed, relatively short-lived uranium isotopes appear. The radioactivity of these isotopes by α-decays exceeds the traditional one by thousands of times. This fact is partly the result of the accumulation of ^{232}U, the concentration of which at the 11th iteration was $3.57\cdot10^{18}$ nuclei/cm^3, while at the end of the traditional fuel campaign for the VVER-1000 reactor model used in this calculation, the concentration of this isotope was approximately $6.4\cdot10^{11}$ nuclei/cm^3. The reason for the discrepancy in the values of ^{232}U concentrations is mainly the presence of accumulated ^{233}U in the fuel, since the (n, 2n) reaction on this nuclide entails an increase in the amount of ^{232}U, based on the calculation, by five orders of magnitude. A more detailed study of this issue is required, since the remaining radioactivity from fission fragments that could not be removed is not taken into account as well.

Conclusion

The calculated data allow us to draw the following conclusions:

1. The unloaded fuel, after being purified from fission fragments, is completely reloaded into the reactor, and the amount of ^{235}U added annually turns out to be 1.68 times less than that existing today with an open fuel cycle.

2. The radioactivity of the fuel returned to the reactor is significantly lower ($1.3 \cdot 10^{10}$ Bq/cm^3) than that of the U-Pu fuel returned to the thermal reactor in the case of a two-component fuel cycle based on uranium-plutonium MOX fuel ($6.4 \cdot 10^{11}$ Bq/cm^3).
3. The uranium isotopes with masses 234 and 236 formed in the fuel tend to the state of saturation and, therefore, the process of returning U-Th fuel can be carried out during the entire life of the reactor.
4. In addition to almost doubling the required loading of ^{235}U, the proposed fuel option and loading schemes do not leave heavy nuclei in storage facilities and significantly reduce the amount of stored SNF radioactive nuclides. However, it should be noted that annually about 100 tons of depleted uranium will be shipped to storage facilities for the preparation of ^{235}U. This uranium will be used in a two-component fuel cycle with U-Pu fuel.
5. The cost of additionally loaded high-enriched uranium is lower than that of low-enriched uranium when traditional uranium fuel is used, which possibly compensates for the unlikely costs of organizing work to load the "fresh" proposed TORUR-5 fuel.

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