Advanced fusion technology in a future nuclear energy system

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Abstract. The paper is concerned with an alternative to the existing concept of expanding the nuclear energy fuel resources in terms of fissile isotopes by producing ^{233}U from ^{232}Th in fusion reactor blankets. The new concept offers several advantages, including a substantial decrease in the risks of environmental pollution due to the low radioactivity of the recycled fuel. The study focuses on several scenarios for the development and use of a new fissile isotope in thermal neutron spectrum reactors (pressurized water reactors) and demonstrates the possibility of closing the fuel cycle in a system of thermal reactors with a fusion neutron source using heavy nuclei.

1 Introduction

The main driving forces behind the current trends in the expanding global economy are population growth, convergence in the levels of specific energy consumption in various countries, and increasing use of energy in the production of goods and services. The past 60 years have seen a 2.3-fold increase in population, a 3.7-fold rise in primary energy consumption, and a 1.6-fold growth in the use of energy. Most forecasts assume a continuation of this trend, with the minimum level determined by a two-fold increase in primary energy consumption with respect to the current value until the end of the century.

Human impacts on climate will be of particular importance. In this context, the idea of the harmful effects of greenhouse gases and especially carbon dioxide is actively promoted, although there is no convincing evidence supporting this claim and the fact that everything will return to how it was when the amount of carbon dioxide in the atmosphere decreases. Nevertheless, the World Energy Agency has published development scenarios focused on the use of low-carbon technologies [1, 2] and none of the development options involves large-scale development of nuclear energy. Despite the fact that electricity generation at nuclear power plants is accompanied by carbon dioxide emissions 160 times less than that using natural gas and that the carbon footprint from nuclear power plants [33is tens times less than from priority solar and wind power plants, the share of nuclear energy in all development scenarios is no more than 10-15%. As for Russia, expanding generating capacity through nuclear power plants can save up to 50 billion m3 of natural gas annually, which allows not only maintaining the volume of exports but also increasing it.

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Currently, the most significant factors hindering the development of nuclear energy are the following: the possibility of radioactive contamination of the environment due to a severe accident, the need to create a radiation-hazardous closed fuel cycle, and a long period of return on investment in nuclear power plants.

2 Some risks of the nuclear power system

It is expected that by 2050, 37 nuclear reactor units of various types will be operating in Russia. The total installed capacity will be about 40 GW. It is mainly planned to build VVER-1200 (Pressurized Water Reactor -1200) [4] and VVER-TOI (Pressurized Water Reactor - Universal Optimized Digital) [5].

The development of large-scale nuclear energy reveals the problem of fuel supply. Currently, the solution of this problem is seen in the development of fast reactor technology capable converting the natural isotopes 238U and 232Th into fissile 233U and 239Pu. Such an organization of the fuel cycle inevitably entails the need for spent nuclear fuel recycling, the scale and intensity of which depend primarily on the rate of energy development. The experience of spent nuclear fuel (SNF) recycling dates back to the creation of nuclear weapons [6]. In contrast to civilian recycling, fuel with low burnup and a small quantity of fission products was recycled. Currently, there is no extensive practice of using spent nuclear fuel and isolating useful isotopes from it [3]. In addition to obvious economic reasons, there are objective physical reasons that hinder the development of spent nuclear fuel recycling. They are associated with the accumulation and spread of radioactivity outside controlled channels of its distribution. The fact is that any of the existing spent fuel recycling schemes implies several channels for the placement of released stable and unstable isotopes. Most of the fissile and non-fissile isotopes enter the first channel, fission products and some unstable isotopes are sent to the second channel. They will be glazed and sent for burial. In addition to these channels, which contain the majority of all chemical elements, there is another one, which is formed due to irretrievable losses. Irretrievable losses arise as a result of radioactive isotopes getting on the floors and walls of working rooms, external surfaces of equipment, technological channels, furnaces, crucibles, molds, etc. [3]. These include very small number of all chemical elements contained in spent nuclear fuel. The very name irretrievable losses suggests that these losses are beyond technological control. Produced during the recycling of spent nuclear fuel, they settle in places that are impossible to determine, or their density is so low that it is impractical to extract them. At the same time, if it is possible to control or isolate them, then such losses cannot be called irretrievable. Irretrievable losses are typical of all production processes involving the extraction or separation of elements. It is difficult to determine their exact value, but it is always other than zero and strongly depends on the technology. It is currently believed that the loss of unstable fission products during spent fuel recycling is slightly less than 1%. Based on the calculation results [4], it is possible to estimate the value of irretrievable losses at about 0.5%; a value used for long-term estimates is of no more than 0.1% [5].

In [7], the example of 90Sr, which has a half-life of 28.78 years, was used to assess the consequences of large-scale recycling of spent nuclear fuel. The study assumes that in the long term, irretrievable losses will amount to 0.1%. During SNF recycling, the amount of isotope that enters the irretrievable loss channel will gradually increase due to the arrival of new portions and decrease due to radiation decay. After some time, equilibrium will be established, i.e., the rate of entry will be equal to the rate of decay. This state will be characterized by constant radioactivity. It is shown in [7] that for a level of irretrievable losses equal to 0.1%, the equilibrium amount will be more than 4% of the total amount of recycled SNF in the annual volume. This will be equivalent to 4.8·1015 Bq. Let us explain this. A 1 GW(e) reactor burns about 1 ton of fissile isotope to operate throughout a year. The yield

of 90Sr from nuclear fission is approximately 6%. Thus, about 23 kg of this isotope will be accumulated annually. The activity of 1g of 90Sr is equal to 5.2·1012 Bq/g, which means that the activity of the annual SNF will be 1.2·1017 Bq and that of the irretrievable losses will be 1.2·1014 Bq. The equilibrium state is 40 times more. It appears that after 100 years of recycled fuel of 25 reactors recycling, radioactivity of 1 will be irretrievably lost. In comparison, the activity of natural uranium "when co-extracted from ore with long-lived members of the radioactive families 238U (230Th, 228Ra) and 235U is 3.46·1013 Bq (1.92·1011 Bq/t [8]). Thus, the radiation background from irretrievable losses of 90Sr alone will be more than 100 times more than the radiation background from uranium with accompanying isotopes extracted from the earth. The study presented in [7] indicates that the radioactivity of 137Cs (5.65·1015 Bq) included in irretrievable losses corresponds with the radioactivity from irretrievable losses of 90Sr. Only 2 of these isotopes will lead to an excess of background radiation compared to natural uranium by almost 300 times over 100 years. When PWR fuel recycling, irretrievable losses will amount up to 10% of the plutonium released during annual recycling, and in case of recycling of fast reactor fuel, the amount of plutonium will be 150% of its annual recycling. Undoubtedly, over time, activity of each individual portion of isotopes will go down, but with the development of large-scale SNF recycling, the number of portions will increase, and, in equilibrium, the scale of radioactivity will be significant.

Figure 1 illustrates the process of radioactivity accumulation in the irretrievable loss channel.

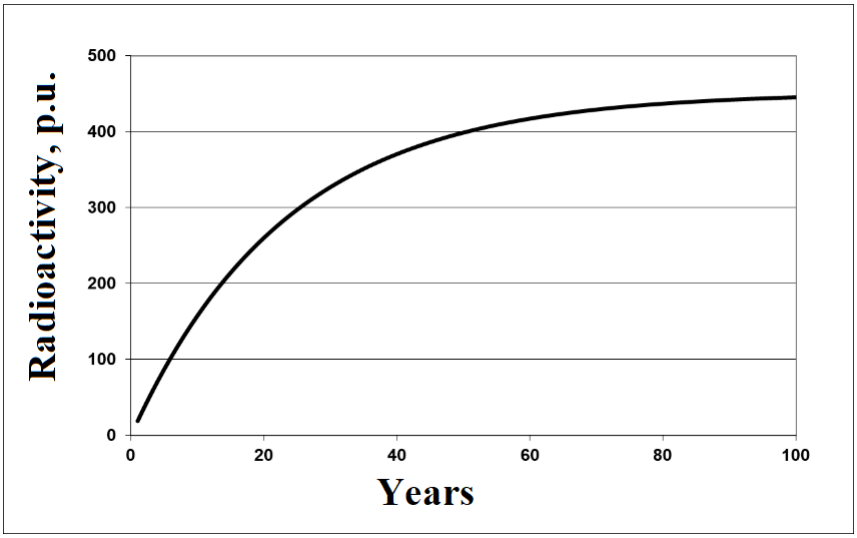

Fig. 1. Radioactivity accumulated in irretrievable losses (0.1%) after recycling spent fuel of PWR with respect to its annual demand for natural uranium [7].

Now the background values of global radiation pollution are 0.045 Ci/km2 for 90Sr, 0.08 Ci/km2 for 137Sc, and 0.005 Ci/km2 for 239Pu [9]. For a nuclear energy system with a scale of only 2 times larger than the existing one with spent fuel recycling, radiation pollution only due to irretrievable losses will reach the values up to 0.248 Ci/km2 for 90Sr, up to 0.55 Ci/km2 for 137Sc, and 0.0091 Ci/km2 for plutonium (only for PWR-1000 SNF). Such a scale will lead to significant radiation pollution of the planet. This result, obtained under the most optimistic assumptions about the organization of spent fuel recycling, does not add arguments in favor of a fuel cycle based on the recycling of fission reactor spent fuel. Today's

practice of recycling technologies evaluates irretrievable losses on a percentage scale, i.e., in real life, radiation pollution will be orders of magnitude greater than current levels.

The literature we have reviewed lacks a detailed discussion of issues related to the formation, propagation, and influence of irretrievable losses on the radiation situation. Given the magnitude of potential pollution, it will be imperative that we address the matter of irretrievable losses.

An acceptable level of radiation load can be achieved by reducing the losses by at least 100 times, which raises the question of technologies that have yet to be created and proven to work.

3 Alternative fuel supply technologies

The radiation load can be reduced in another way, i.e., by recycling of low-activity fuel. This path will require storing the fuel for at least 200 years. During this time, the number of dangerous unstable isotopes will decrease 100 times. This method, however, is unacceptable for the technology of fast reactors, for which long-term spent fuel storage essentially means working in an open fuel cycle, which will significantly increase the consumption of natural uranium compared to the current level.

Recycling of low-activity fuels can be feasible if the production of fuel isotopes from raw materials and fission products is spatially separated. This can be achieved using a fusion reactor. The raw isotope will be placed in the blanket of this reactor and neutrons will enter the blanket from the core of the fusion reactor. This idea was expressed by I.V. Kurchatov in the middle of the last century [10]. The study [11] indicates that when 1 g of new fuel isotope is isolated, the amount of radioactivity in the form of unstable nuclei is approximately 100 times more for spent fuel of fission reactor than for a fusion reactor blanket.

The papers [7, 11–15] center on possible scenarios for organizing the fuel cycle for nuclear energy with the fusion reactors. Estimates of radioactivity arising when spent nuclear fuel is recycled to obtain 1 g of fissile isotope are shown in Figure 2.

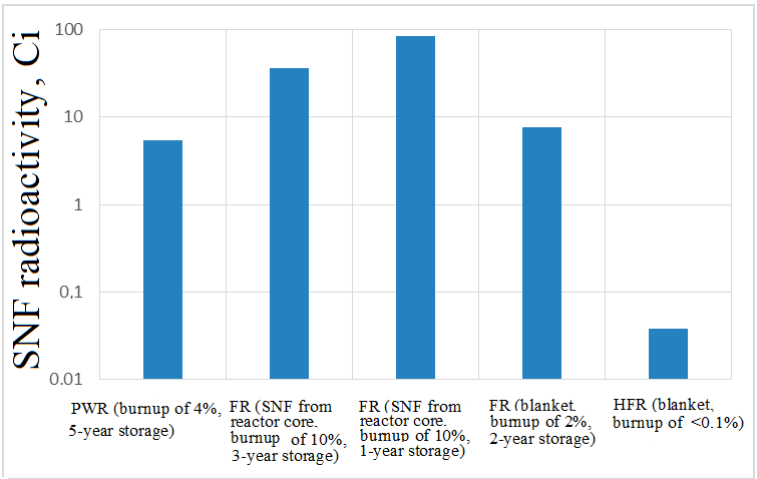

Fig. 2. Spent nuclear fuel radioactivity, which must be handled to obtain 1 g of fissile isotope, for various types of reactors.

The papers [11, 12] highlight the risks of implementing scenarios that use regenerated uranium and recycled spent fuel from fission reactors powered by ^{233}U. In addition to the obvious advantages of significantly reducing the volume of stored spent fuel, one cannot neglect the risks associated with the radioactivity released during the SNF recycling.

Figures 3 and 4 present results of comparative calculations carried out in [11, 12] for scenarios of closing the fuel cycle with the spent fuel recycling for PWR-1000 powered by fuel with ^{235}U and advanced fuel based on ^{233}U.

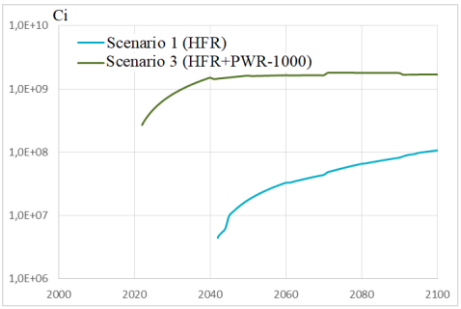

Fig. 3. Radioactivity discharged in scenarios with and without PWR-1000 SNF recycling for ^{235}U.

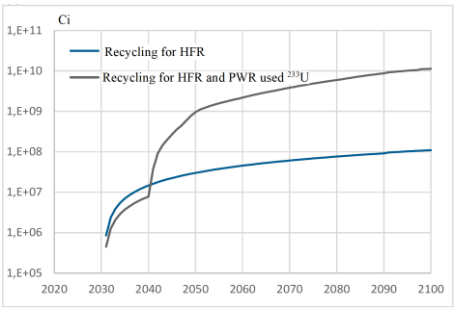

Fig. 4. Radioactivity released in scenarios with and without PWR-1000 SNF recycling for ^{233}U.

4 Some fuel cycle options for FNS+PWR

The calculation models of the nuclear energy system elements considered below are built using MCNP 5 code [16], which estimates the average neutron flux density in a molten-salt thorium blanket (LiF - ThF_4). The obtained neutron flux density and spectrum-averaged cross sections for neutron reactions were subsequently used to estimate the equilibrium quantities of nuclides established in the fusion neutron source (FNS) blanket under various operating conditions. The equilibrium state of the nuclear power system was calculated in the ISTAR code [17-19]. It is important to note that modeling of the equilibrium state of a nuclear power system using the ISTAR code allows estimating the equilibrium quantities of all heavy nuclides that, in principle, can be accumulated in the system. This becomes possible because the ISTAR code considers the complete matrix of nuclide transitions, which describes all chains of transformations. The issue of the time required to achieve equilibrium quantities in the nuclear energy system is not considered in this work.

The ISTAR code considers nuclear energy as a set of elements characterized by an average neutron flux density (can be equal to zero), a neutron spectrum (taken into consideration through a set of spectrum-averaged neutron cross sections), and rates of nuclide exchange with other elements of the nuclear fuel cycle (reactors of various types, storage facilities, recycling facilities, etc.).

A diagram of one of the possible options for organizing of a fuel cycle based on FNS and PWR is presented in Figure 5. The considered option of the fuel cycle with FNS and thermal neutron reactors does not involve isotope separation. The FNS blanket and thermal reactors exchange chemical elements through the fuel cycle, the isotopic composition of which is determined by the irradiation conditions and fuel cycle length.

In the fuel cycle under study, in accordance with the scheme, it is planned to produce ^{233}U in the FNS blanket to load it as a fissile isotope into 500 MWe and 1000 MWe pressurized water reactors. The FNS power assumed to be 100 MW, given the thermonuclear neutron energy of 14 MeV, uniquely determines the intensity of the emission of thermonuclear neutrons into the blanket ($4.46 \cdot 10^{19}$ n/s).

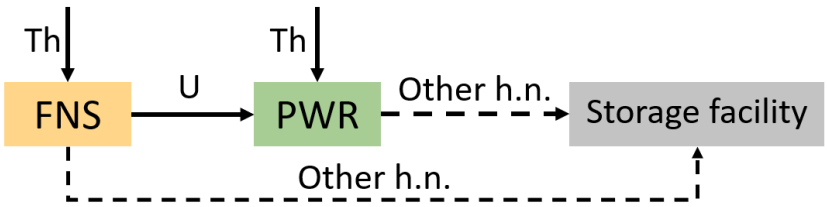

Fig. 5. Scheme of the nuclear fuel cycle under study, where FNS is a 100 MW fusion neutron source; PWR – pressurized water reactor, U – uranium, Th – thorium, other h.n. – other heavy nuclei.

The feasibility of such a cycle and its effectiveness can be evaluated by varying the rate of transfer of the uranium produced in the FNS blanket to the PWR and the starting uranium content in the PWR fuel, as well as by changing the installed capacity of the reactor.

The study assumes that thorium and protactinium return from the external fuel cycle to the FNS blanket, whereas all other heavy nuclei, including minor actinides, formed in the fuel cycle of the FNS blanket, are placed into storage. The loss of heavy nuclei is compensated by the feed of 232Th. These calculations are focused on the balance of heavy nuclei only (fission products were not considered). It is worth emphasizing that the quantity of minor actinides accumulated in the uranium-thorium fuel cycle is significantly less than in the uranium-plutonium fuel cycle.

The study examined the FNS operating conditions under which only uranium is removed from the fuel, since this option of uranium production from the molten salt is easier to implement (bubbling fluorine through the molten salts that make up the FNS blanket). In the case when the entire volume of the loop is processed once every two years, the neutron flux density in the FNS blanket is 3.7·1013 1/(cm2/s).

The behavior of a reactor in a nuclear power system is described by the average neutron flux density and the set of reaction rates (neutron spectrum) [17, 19, 20]. These characteristics for a pressurized water reactor with thorium-uranium fuel were assessed when calculating the change in the isotopic composition of the PWR-1000 fuel assembly located in the neutron field for a time equal to the fuel lifetime.

The burnup of fuel assemblies with enriched uranium dioxide fuel containing the isotopes 235U (4.7%) and 238U with a duration of 990 effective days (3 steps of 330 days each) was calculated. Such fuel will be further called standard fuel. The principle of calculating the fuel cycle during partial refueling involves estimating kres, i.e., the multiplication factor of all fuel at the end of the fuel cycle [21]. In the simplest case, this factor is estimated as the average between the multiplication factors of different fuel compositions, differing in burnups, obtained by the end of the reactor lifetime. The value of kres should slightly exceed unity by the amount of reactivity margin for neutron leakage from the reactor core. In order to compare different options of PWR fuel cycles, burnup calculations were performed in which the starting content of fissile nuclei was selected so as to provide close or equal values of kres. The value of kres for a pressurized water reactor with a starting content of the 235U isotope equal to 4.7%, which operates under three-fold partial overloads every 330 days, is 1.049 and it is assumed as a reference value.

Burnups of two fuel assembly options are calculated for PWRs of various powers with uranium-thorium loading. The 233U enrichment was selected so as to obtain kres consistent with the value obtained with standard uranium fuel. The findings indicate that for PWR-1000 with a starting uranium content of 3.8 wt.%, kres is 1.051, and for PWR-500 with that of 2.9 wt.%, kres is 1.048. The change in keff as a function of time is presented in Figure 6.

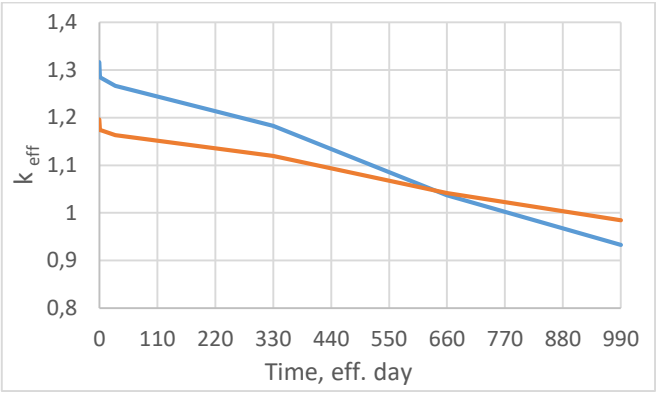

Fig. 6. Graph of changes in k_{eff} over time for different powers of the PWR reactor: — PWR-1000; — PWR-500.

In the course of calculating the burnup of fuel assemblies with uranium-thorium fuel, sets of spectrum-averaged isotope cross sections were generated, which were subsequently used to calculate the equilibrium fuel compositions.

Let us consider the specific features of the nuclear fuel cycle organization diagram shown in Figure 5 for two unit capacities of pressurized water reactor. Nuclide exchange for each component of the system occurs through an external fuel cycle, which has no neutron field and where some of the isotopes are released from the installation at a certain rate. The rate of isotope transfer depends on the duration of the fuel lifetime and the processing rate. All uranium isotopes produced in the FNS blanket are transferred to the fuel cycle of the pressurized water reactor at a rate of 0.5 equilibrium quantities per year. At the same time, other heavy nuclei, including a small number of minor actinides (the rate of their generation is indicated in Table 1) are accumulated in the storage facility. The lack of heavy nuclei is compensated by feeding 232Th. In the reactor, all isotopes of thorium, uranium, and protactinium return to the core through the external fuel cycle, and the remaining heavy nuclei are assumed to be removed to storage at a rate of 1/5 of the equilibrium quantities per year, which corresponds to the duration of the external fuel cycle of 5 years. With a fuel lifetime of 3 years, 1/3 of the reactor core is removed from the reactor annually, i.e., a third of the number of heavy nuclei loaded into the reactor. The main operating parameters of such a cycle for different reactor powers are presented below (Table 1). Table 1 shows the total power and makeup of nuclear power system elements, which may correspond, for example, to one or several pressurized water reactors of a given power.

Table 1. Main characteristics of nuclear fuel cycle systems.

Parameter	FNS – PWR-1000		FNS – PWR-500	
	FNS blanket	PWR-1000	FNS blanket	PWR-500
Makeup ^{232}Th, kg/year	477.8	951.13	477.8	1500.0
Power, MW	73.2	3.435.71	73.2	4775.3
Neutron flux density, 1/(cm^2 /s)	$3.71 \cdot 10^{13}$	$3.41 \cdot 10^{14}$	$3.71 \cdot 10^{13}$	$1.75 \cdot 10^{14}$
Equilibrium quantity, kg				
Total	509.503	848.99	509.503	247.933
^{233}U	723	2.002	723	5.079
^{232}Th	501.651	81.021	501.651	238.724

^{233}Pa	40	94	40	149
All of U	858	3.687	858	8.896
All of Pa	5.366	104	5.366	175
Minor actinide generation rate, kg/GW(t)/year	6.9		7.4	

When used in a PWR-1000 system, one FNS blanket can provide a fuel feed of up to 1.2 of PWR-1000 (one FNS blanket produces 380 kg of ^{233}U per year, with the annual requirement of one PWR-1000 being 315 kg of ^{233}U). In the case of a 2-fold reduction in the reactor power capacity, one FNS blanket can produce fissile isotopes for 3 thermal reactors. This option, however, does not take into account the balance of tritium, which is necessary for the implementation of a fusion reaction and the generation of neutrons in the FNS. The reason for this is the assumption that tritium is produced in the FNS itself, or in the future, tritium will be produced in fission reactors partially using thermal neutrons when replacing boron with ^{6}Li in the reactivity compensators of these reactors.

5 Conclusion

Scenarios for the development of distributed nuclear energy based on medium- and small-power reactors are currently gaining popularity. Furthermore, nuclear energy is called upon to take part in the development of large-scale hydrogen energy. All this will inevitably lead to an increase in fuel consumption, which in turn will result in the closure of the fuel cycle and the involvement of fertile isotopes in it. The severe threat of radiation contamination may require us to stop using of nuclear fuel for energy needs or seek alternative methods to expand the fuel resources. This paper explores the potential of utilizing a fusion neutron source as a viable solution to the nuclear power supply problems.

Following the chosen scheme for organizing the nuclear fuel cycle, consideration is given to an option in which the fusion neutron source produces 233U and transfers all uranium isotopes to the pressurized water reactor at a rate of 0.5 equilibrium quantities per year. Thus, the possibility of closing the fuel cycle in a system of thermal reactors with a fusion neutron source using heavy nuclei has been demonstrated, when one fusion neutron source can produce enough fissile isotopes to feed 1.2 of PWR-1000 reactors. With the starting fuel load maintained, a two-fold reduction in the power unit capacity (and, consequently, the burnup) of a pressurized water-type reactor leads to a blanket/reactor ratio of 1/3, which allows, with unchanged blanket characteristics, increasing the installed capacity of the system by 40% with a slight increase in the number of minor actinides produced per 1 GW.

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