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POTENTIAL ROLE OF FUSION NEUTRON SOURCE IN NUCLEAR POWER SYSTEMS

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The paper analyzes the possibility of integrating hybrid thermonuclear reactors (HTRs) into existing nuclear power systems. This is supposed to involve the production of non-traditional nuclear fuel in a D—T-plasma operated HTR with a thorium blanket. Non-traditional fuel to be produced is peculiar in that it contains in significant amounts of rare isotopes, such as ^{231}Pa and ^{232}U, alongside the traditional ^{233}U. High-energy (14.1 MeV) thermonuclear neutrons have a unique ability to promote the accumulation of significant amounts of ^{231}Pa and ^{232}U via threshold (n, 2n)- and (n, 3n)-reactions. Non-traditional fuel compositions for nuclear power thermal reactors (the most common nuclear reactor class in the world), hold promise due to the following factors. As is known, the neutron balances for reactors fueled with ^{235}U are better (in terms of the breeding ratio enhancement) than for reactors fueled with ^{233}U or reactor-grade plutonium. A better neutron balance is likely to translate into higher fuel breeding ratios and help ease the thermal reactors' fuel self-sustainability problem. Because ^{231}Pa and ^{232}U are fertile and moderately fissionable nuclides, they can stabilize the time-dependent behavior of the thermal reactor power and prolonging a thermal reactor's lifetime through higher fuel burnup. Being a strong α-emitter, ^{232}U can be used to control unauthorized use of ^{233}U-based nuclear explosives and thereby contribute to nuclear non-proliferation. All this suggests that D—T-plasma operated HTRs with a thorium blanket can be integrated into nuclear power systems to generate very promising non-traditional fuel compositions for conventional nuclear power reactors.

Key words: hybrid thermonuclear reactor, fusion neutron source, thorium blanket, ^{231}Pa and ^{232}U.

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ПОТЕНЦИАЛЬНАЯ РОЛЬ ТЕРМОЯДЕРНОГО НЕЙТРОННОГО ИСТОЧНИКА В ЯДЕРНЫХ ЭНЕРГЕТИЧЕСКИХ СИСТЕМАХ

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Анализируется возможность включения гибридных термоядерных реакторов (ГТР) в существующие ядерные энергетические системы. Предлагается наработка нетрадиционного ядерного топлива в ториевом бланкете ГТР на (D—T)-плазме. Особенность нарабатываемого нетрадиционного топлива заключается в значительном количестве таких редких изотопов, как ^{231}Pa и ^{232}U. Только термоядерные нейтроны высоких энергий (14,1 МэВ) могут обеспечить накопление значительных количеств ^{231}Pa и ^{232}U через пороговые (n, 2n)- и (n, 3n)-реакции. Изотопы ^{231}Pa и ^{232}U, являясь сырьевыми и умеренно делящимися нуклидами, способны стабилизировать размножающие свойства ядерного топлива и обеспечить достижение сверхглубокого выгорания. Изотоп ^{232}U, являясь интенсивным источником α-частиц, способен предотвратить любые попытки несанкционированного использования ^{233}U в оружейных целях, т.е. ^{232}U может усилить режим ядерного нераспространения. Таким образом, ГТР на (D—T)-плазме с ториевым бланкетом можно использовать для наработки перспективных топливных композиций для традиционных ядерных энергетических реакторов.

Ключевые слова: гибридный термоядерный реактор, источник термоядерных нейтронов, ториевый бланкет, ^{231}Pa, ^{232}U.

INTRODUCTION

Thermonuclear reactors (TRs) have gone through several development stages. Initially, they were looked upon as just sources of energy, to be generated solely by fusion reactions between light isotopes. Such TRs are dubbed «pure TRs». Their attractiveness is based on the following:

— safety, as there is no way for uncontrolled power excursion (possible in fission reactors) to occur;

— unlimited fuel supply, especially when using heavy hydrogen isotopes;

— no high activity, long-lived nuclear waste (the only issue is neutron-induced radioactivity in fusion structural materials).

However, there are many physical and engineering challenges in implementing stand-alone TRs. This gave rise to the idea of combining fusion and fission into a nuclear facility with a fusion plasma core surrounded by a blanket of heavy fissile materials (the so-called «hybrid thermonuclear reactor», HTR). In a HTR, thermonuclear plasma acts mainly as a source of neutrons for the blanket, where most of is generated. The blanket operates as a subcritical system, which allows the pure TR's first fundamental strength, safety, to be preserved. Unfortunately, the TR's two other strengths, the unlimited fuel supply and absence of radioactive wastes, are lost in the HTR. However, as in the case of a pure TR, the development of a HTR is confronted with many physical and engineering obstacles. They are related to the HTR concept, according to which most of energy is generated by fission reactions in the HTR blanket, while thermonuclear fusion reactions play the role of an energy release control tool, needed to provide safe HTR operation and enable a practically instant shutdown whenever need arises.

The same function in nuclear fission reactors is performed by numerous control and safety systems. To sum it up, combining fusion and fission in one power facility is a daunting task. Indeed, current HTR projects are lagging behind nuclear power reactors in terms of economic competitiveness.

In the past few years, HTR projects have been developed, in which hybrids are used for breeding fissile materials for nuclear power reactors [1, 2] rather than energy generation. In such projects, a HTR is used as a fusion neutron source (FNS), and its blanket has to be filled with fertile materials, such as natural uranium, depleted uranium and natural thorium.

Historically, the world nuclear power industry has been using natural uranium as a primary source of fuel. Therefore, blankets of natural or depleted uranium have been traditionally used to breed plutonium. From the viewpoint of neutron physics, plutonium the best choice as material for fast breeder reactors (FBRs), which, according to Russia's 2018 Strategy for Nuclear Power Development throughout this century are one of the pillars of the nuclear power industry in this country [3]. However, it should be kept in mind that thermal reactors, primarily light-water reactors (LWRs), are today the most common nuclear power generating units in the world, including Russia [4]. Although intensely developing and advancing, FBRs are less effective economically than thermal reactors. Strategy-2018 includes the scenarios of a two-component nuclear power system consisting mainly of thermal reactors, supplemented by FBRs. Unfortunately, present-day thermal reactors have fuel breeding ratios (BRs) of about 0.5, which prevents them from being self-contained and generating their own fuel. Two advanced thermal reactors have been implemented, namely, an LWR with a controlled neutron spectrum and the SLWR with supercritical-pressure light water-cooled reactors (SCLWR). Their BRs are 0.6—0.7 and 0.8—0.9 respectively. As one can see, thermal reactors need to add just a little to their BRs to catch up with FBRs (whose typical BRs are ≥ 1). It is this small deficiency that can be accommodated by using the FNS blanket.

As is known, isotope ^{233}U is more effective than ^{235}U and plutonium in terms of maintaining the thermal reactor neutron balance. ^{233}U can accumulate in the FNS thorium blanket. Unfortunately, natural thorium, like rare-earth elements, is strongly dispersed in the natural environment, and there are no Th-rich ores or deposits. So far, natural thorium is recovered at a low cost as a by-product (even waste) of rare-earth mining. Russia's natural thorium inventory is estimated at 6,000 metric tons (MT) [5], roughly equivalent to Russia's 2-year production of natural uranium. Natural thorium can be used as a fertile material and converted to fissile isotope ^{233}U in the FNS thorium blanket.

Let us consider a scenario where thorium is no longer mined, and only a limited thorium inventory of 6,000 MT is available. In these circumstances, only a small part (say, one-tenth, or around 600 MT) of this inventory can be converted into ^{233}U, as the rest would be required to fill the FNS blanket.

As is known, the electrical power of Russian nuclear power plants (NPPs) totalled around 30 GW(e) installed capacity in 2020. A 1 GW(e) thermal reactor burns 1 MT of fissile isotopes annually and accumulates 1 MT of fission products. Consequently, Russian NPPs' total demand for ^{233}U can be ~30 MT a year. Conclusion: Russia's current natural thorium inventory is sufficient to supply all the country's NPPs with ^{233}U for 20 years — even if the «open» or «once-through» nuclear fuel cycle is used. If a system consisting of thermal reactors with a BR of about 0.5 and using a closed fuel cycle is employed, the available inventory is enough to meet an up to 40-years' demand. If, in accordance with Strategy-2018, Russia switches over to the closed nuclear fuel cycle with SCLWRs (BR ~ 0.8—0.9) introduced in a span of 25—35 years, then this inventory will last for 100—200 years. One SCLWR will consume ~100—200 kg Th per GW(e) year**.** This means that only 3—6 MT of natural thorium will have to be mined annually to supply Russian NPPs with their total installed capacity of ~30 GW(e). This seems practicable, considering that Russia' thorium mining capacities will only account for 0.1—0.2% of its current uranium mining capacities. With Russian NPPs' total installed capacity tripling to 90—100 GW(e) in accordance with Strategy-2018, the total demands for mined thorium will increase to 9—18 MT a year by the end of the century. In that case, thorium production will be 0.3—0.6% of the current uranium production, which, again, seems accomplishable.

In regard to the potential use of thorium-based fuel cycles to support future requirements of nuclear power systems, it is appropriate to highlight the following two specific aspects.

The first has to do with the required scale of deploying thorium mining capacities and infrastructure. The example of the small thorium inventory in Krasnoufimsk, Russia, demonstrates, how salient the impact of tapping this source could be, even at an early stage, and how the first steps in harnessing the thorium potential can be made. It is noteworthy that Russia’s available thorium inventory is insufficient for loading thermal and fast nuclear power reactor cores, but adequate for filling thermonuclear reactor blankets.

The second important aspect is related to international affairs. BRICS, the association of five major emerging economies (Brazil, Russia, India, China and South Africa) was founded in 2006 at Russia’s initiative to coordinate economic activities of the member nations. Brazil, India and South Africa have large geological reserves of natural thorium [6, 7]. Brazil and India use their well-explored reserves of natural thorium and rare-earth elements mainly to recover rare-earth elements, while thorium is produced as a by-product and put in storage for future use. In this context, Russia benefits from its membership in the BRICS, as this opens up the opportunity for it to incorporate imported thorium into its nuclear fuel cycle without conducting exploration and establishing costly mining and processing facilities. Such cooperation can be used as a way to save efforts needed to incorporate natural thorium resources into nuclear power systems of Russia and other BRICS countries within the framework of international collaboration.

SELECTION OF PLASMA COMPOSITION FOR FUSION NEUTRON SOURCE

The following nuclear reactions can take place in thermonuclear D—D-plasma:

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + n\ (14.1\ \mathrm{MeV});$$

$$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + p;$$

$$\mathrm{D} + \mathrm{D} \rightarrow 50\%\colon {}^{3}\mathrm{He} + n\ (2.5\ \mathrm{MeV});$$

$$\mathrm{D} + \mathrm{D} \rightarrow 50\%\colon \mathrm{T} + p.$$

Fusion of two deuterium nuclei can produce, with a 50% probability, either one neutron with a relatively high energy (2.5 MeV), plus one ^{3}He nucleus, or one tritium nucleus plus one proton. The produced nuclei (^{3}He and tritium) are highly likely to enter into concomitant thermonuclear reactions with deuterium nuclei. This is due to the fact that the probability of the D—^{3}He- and the D—T-reactions is one and two orders of magnitude, respectively, higher than for the original D—D-reaction. The micro cross-sections of these three thermonuclear reactions are shown in Fig. 1 as functions of the energy of D, ^{3}He and T relative motions. The micro cross-sections of the ^{235}U fission reaction as a function of neutron energy are presented in the same figure for comparison.

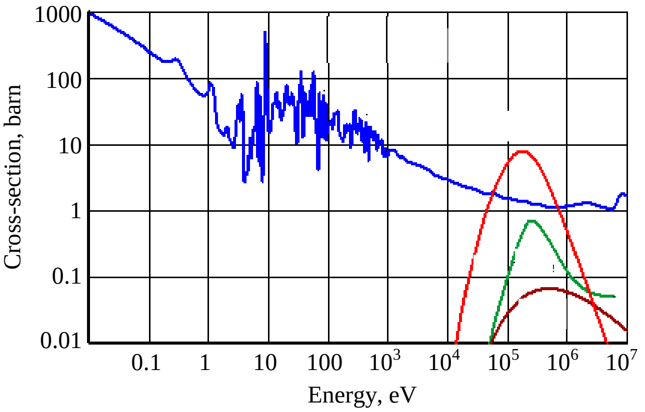

Fig. 1. Micro cross-sections of the ^{235}U fission reaction as a function of neutron energy and micro cross-sections of three thermonuclear reactions of light nuclei as functions of the energy of D, ^{3}He and T relative motions: ——— ^{235}U fussion, ——— D—T, ——— D—^{3}H, ——— D—D

One basic D—D-reaction and two concomitant reactions can produce 0.5 neutron (of 2.5 MeV) and 0.5 neutron (of 14.1 MeV) on average. The density of plasma is seven orders of magnitude lower than typically for solid materials. The magnetic field used for plasma confinement is unable to retain uncharged neutrons. That is why thermonuclear neutrons are highly likely to escape from both plasma and the FNS. In the case of D—T-plasma, a single D—T-reaction produces one high-energy (14.1 MeV) neutron.

Using D—T-plasma instead of D—D-plasma seems appropriate for the following two reasons. Firstly, the micro cross-sections of the D—T-reaction are two orders of magnitude larger than for the D—D-reactions. This suggests that the construction and starting up of a thermonuclear reactor operated with D—T-plasma would be much easier. Secondly, the D—T-reactions can emit twice as many high-energy (14.1 MeV) neutrons than D—D-reactions. These high-energy neutrons are able to produce, by neutron irradiation of natural thorium in the HTR blanket, one ‘traditional’ fissile isotope ^{233}U and two ‘non-traditional’ but very promising isotopes ^{231}Pa and ^{232}U. As shown in [8—10], ^{231}Pa can stabilize nuclear fuel’s neutron-multiplying properties (the result being a deeper fuel burnup and a longer fuel lifetime), while ^{232}U can provide proliferation protection of ^{233}U-based fuel compositions.

When using D—T-plasma, HTR operators have to handle radioactive tritium (whose half-life is 12.3 years). So, tritium remote handling technologies must be worked out and implemented. Tritium does not exist in the nature because of its relatively short half-life. Significant tritium quantities can be produced by neutron irradiation of Li-containing materials in HTR via the ^{6}Li(n, α)T-reaction.

Because one tritium nucleus is consumed in the ^{6}Li(n, α)T-reaction to breed one high-energy neutron, and because another neutron is needed to produce a new tritium nucleus via the same reaction, one may get a wrong impression that all thermonuclear neutrons need to be used to replenishing the burnt tritium, and that there are no neutrons left to produce new fissile materials. In reality, high-energy thermonuclear neutrons can be intensely multiplied by threshold (n, 2n)- and (n, 3n)-reactions with a multiplication factor of about 1.5. Reproduction of one tritium nucleus requires slightly above one neutron (roughly, 1.06 neutrons with account taken of reprocessing losses and tritium’s short half-life). According to approximate evaluations, about 0.15 neutrons will be absorbed by HTR coolant, neutron moderator, structural materials, and lost as a neutron leakage. So, only 0.3 neutrons from one D—T-reaction may be used to produce new fissile materials.

The FBRs’ breeding ratio reaches unity, i.e. excessive neutron amount in the FBR is three-fold larger than in a HTR operated with D—T-plasma. However, one excessive neutron in the FBR is produced by fission reaction with an energy release of 200 MeV. One D—T-reaction in HTR can only produce 0.3 excessive neutrons. One D—T-reaction releases some 21 MeV of energy (roughly, ten times lower), with account taken of γ-rays and the capture of radiative neutrons in the Th-blanket. If the FBR and HTR thermal powers are the same, then a D—T-plasma-operated HTR can produce more (3x) fissile than FBR.

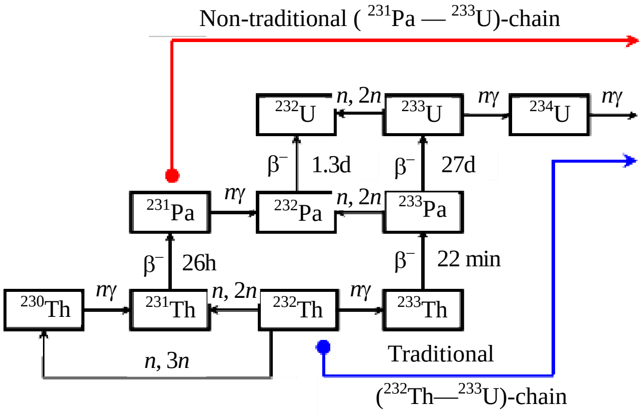

Fig. 2. Chains of isotopic transformations in the fuel (Th—U)-cycle

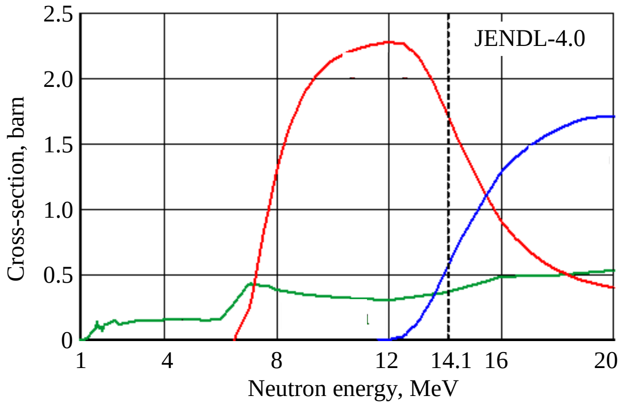

Fig. 3. Micro-cross-sections of fission, (n, 2n)- and (n, 3n)-reactions involving ^{232}Th: ——— (n, 3n), ——— (n, 2n), ——— fission

The following facts are worthy of note. Mean neutron energy in the FBR is around 0.1 MeV. Mean neutron energy in the spectrum of fission neutrons is about 2 MeV. Mean energy of spallation neutrons in accelerator-driven facilities varies from 1 to 10 MeV. Therefore, thermonuclear neutrons emitted by D—T-plasma in HTR have the highest energy (14.1 MeV). This huge energy potential can be employed to produce «non-traditional» isotope compositions containing ^{233}U, ^{231}Pa and ^{232}U, intended for introduction into fresh fuel, to be used in traditional thermal reactors. Shown in Fig. 2 are the key, most effective, chains of isotopic transformations associated with neutron irradiation of the thorium blanket.

As is seen, isotopes ^{231}Pa and ^{232}U are produced by threshold (n, 2n)- and (n, 3n)-reactions, which can only be initiated by high-energy neutrons. Micro cross-sections of ^{232}Th(n, f), ^{232}Th(n, 2n)- and ^{232}Th(n, 3n)-reactions are shown in Fig. 3.

As indicated in the figure, the probability of necessary threshold (n, 2n)- and (n, 3n)-reactions in the high-energy neutron region (above 7 MeV) is larger than for fission reactions. Then it is possible to produce non-traditional isotopes with little heat generation in the thorium blanket, which is important from the blanket engineering prospective (this may substantially facilitate the development and implementation of HTR projects). Thus, high-energy (14.1 MeV) thermonuclear neutrons emitted by D—T-plasma make it possible in principle to produce non-traditional isotopes. As is known, ^{232}Th is a threshold fissile isotope (Fig. 4). That is why slow neutrons will be mainly absorbed by ^{232}Th to produce ^{233}U after two relatively short β-decays (see Fig. 2).

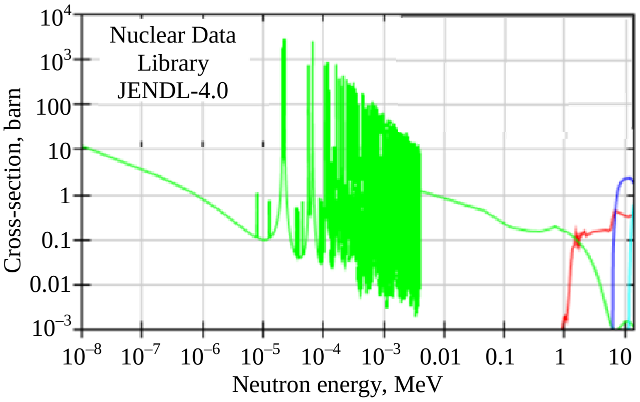

Fig. 4. Micro cross-sections of ^{232}Th: —— — (*n*, 3*n*)-reaction, —— — (*n*, 2*n*)-reaction, —— — radiative capture, —— — fission

The micro cross-sections of neutron ^{232}Th reactions within the energy range from 0.01 eV to 14.1 MeV are shown in Fig. 4 [11, 12]. As is seen, threshold (*n*, 2*n*)- and (*n*, 3*n*)-reactions dominate in the high-energy (above 7 MeV) neutron region, and fission reactions come to prominence in the 2—7 MeV energy range, while the radiative neutron capture comes to the fore in the lower energy region. To sum it up, firstly, non-traditional isotopes ^{231}Pa and ^{232}U can only be produced by high-energy (7—14 MeV) neutrons. Secondly, fission reaction only plays a significant role in a rather narrow energy range (2—7 MeV). Fission reactions can occur with a relatively low probability because fission cross-sections are at the level of decimal barn fractions, which are lower than cross-sections of threshold (*n*, 2*n*)-, (*n*, 3*n*)-reactions and those of radiative neutron capture reactions by an order of magnitude. As a result, heat generation rate in the Th-blanket will be very small. Low-intensity heat generation can simplify the requirements for the thermal-technical equipment needed for heat utilization or removal. Thirdly, slow neutrons (with energies below 2 MeV) can be used to produce fissile isotope ^{233}U, a nuclide better suited for thermal reactors than ^{235}U (from the ‘neutron budget’ viewpoint).

CONCLUSION

If a thorium blanket is used in HTRs to produce fissile materials for nuclear power reactors, then Russia’s available inventories of natural thorium are sufficient to supply national NPPs, even operated under the open fuel cycle conditions, for a long period of time (up to 20 years).

If SCLWRs with a breeding ratio of 0.8—0.9 come into play by the end of the century and operate under the closed fuel cycle conditions, then the demands for mined thorium from Russian NPPs (whose total installed electrical capacity is expected to increase three-fold) will be 0.3—0.6% of the current uranium production.

It seems reasonable to use D—T-plasma in HTRs because, firstly, it may be relatively easily ignited, and, secondly, it can act as a very productive source of high-energy neutrons, which are able to produce non-traditional isotope compositions through threshold (*n*, 2*n*)- and (*n*, 3*n*)-reactions.

An HTR operated with D—T-plasma is able to produce larger (3*x*) amounts of fissile materials than the FBR of a similar thermal power.

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