Physical aspects for involvement of thermonuclear reactors into nuclear power systems

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Abstract. The paper analyzes a possibility to involve hybrid thermonuclear reactors into the existing nuclear power systems. The possibility is related with production of non-traditional nuclear fuel in thorium blanket of hybrid thermonuclear reactors on D-T plasma. Non-traditional peculiarity of such a fuel consists in significant amounts of some non-traditional isotopes, namely $^{231}$Pa and $^{232}$U, together with traditional uranium isotope $^{233}$U in the fuel. High-energy (14.1 MeV) thermonuclear neutrons can provide accumulation of significant $^{231}$Pa and $^{232}$U quantities through threshold (n,2n) and (n,3n) reactions. The promising features of the non-traditional fuel composition for nuclear power thermal reactors, basic component of the existing world-wide nuclear power industry, are defined by the following factors. As is known, $^{233}$U is able to provide more economical neutron balance in thermal reactors than $^{235}$U and reactor-grade plutonium. The better neutron balance can result in higher values of the fuel breeding ratio and, as a consequence, in relaxation of the thermal reactors fuel self-sustainability problem. Isotopes $^{231}$Pa and $^{232}$U, being fertile and moderate fissionable nuclides, are able to stabilize time-dependent evolution of the thermal reactors power, prolong the thermal reactors lifetime through higher values of the fuel burn-up. Isotope $^{232}$U, being intense $\alpha$-emitter, is able to prevent any attempts for unauthorized usage of $^{233}$U in nuclear explosive devices, i.e. $^{233}$U can strengthen regime of nuclear non-proliferation. Thus, the hybrid thermonuclear reactors on D-T plasma with thorium blanket can be involved into nuclear power systems for generation of non-traditional, very promising fuel compositions for traditional nuclear power reactors.

1. Introduction

Thermonuclear reactors in the process of their development have passed a series of steps. At initial stage they have been regarded as energy sources only, i.e. as generators of the energy produced only by fusion reactions of light isotopes. Such thermonuclear reactor may be named as pure thermonuclear reactor. Attractiveness of pure thermonuclear reactor is defined by the following aspects:

- Safe operation because there is no any principal possibility for uncontrolled power excursion in thermonuclear reactor, on the contrary to the situation with operation of nuclear fission reactors;
- Unlimited fuel resources, especially in the case of heavy hydrogen isotopes;
- Absence of radioactive wastes in spent thermonuclear fuel (induced radioactivity of structural materials takes place only).
However, in view of the fact that development of pure thermonuclear reactor has encountered a series of physical and technological difficulties, some specialists have proposed to utilize both thermonuclear energy and nuclear fission energy by surrounding plasma with blanket containing heavy fissile materials. Here thermonuclear plasma acts mainly as a neutron source for blanket where the largest energy fraction is generated. Such thermonuclear reactor was named as hybrid thermonuclear reactor (HTR). Since the HTR blanket is kept in deep subcritical state, then the first principal advantage of pure thermonuclear reactor (safe operation) can be reserved. Unfortunately, two other advantages of pure thermonuclear reactor, namely unlimited fuel resources and absence of radioactive wastes, are lost in the HTR. However, the HTR, like pure thermonuclear reactor, have encountered multiple physical and technological obstacles. Some difficulties were related with the fact that the largest energy fraction is generated by fission reactions in HTR blanket while thermonuclear fusion reactions play a role of a regulatory tool which must provide safe HTR operation with practically instant shutdown whenever need arises. The same mission in nuclear fission reactors is charged to multiple control and safety systems. Thus, at present, combination of thermonuclear fusion reactions and nuclear fission reactions in a single power facility is an extremely complicated problem. Current HTR projects are not able to stand up to nuclear power reactors in their economic competitiveness.

In the last years some HTR projects have been developed not as energy generators but as producers of fissile materials for nuclear power reactors. In this case HTR is transformed into a fusion neutron source (FNS). HTR blanket must be loaded with fertile materials, such as natural uranium, depleted uranium and natural thorium.

Historically, nuclear power systems in the world have been developed with application of natural uranium as a basic nuclear material. So, natural or depleted uranium blanket was traditionally used for plutonium production. From viewpoint of neutron physics, plutonium the very suitable material for fast breeder reactors (FBR) which, according to the State Strategy on nuclear power development in the Russian Federation up to the end of the 21st century [1], are regarded as a basic component of future Russian nuclear power system. However, in today situation, nuclear power thermal reactors, mainly light-water reactors (LWR), constitute a basis of the world-wide nuclear power systems, including Russian nuclear power [2]. Despite intense development and advancement of FBR, they are not able to compete with thermal reactors in economic efficiency. The State Strategy [1] includes also some scenarios of two-component nuclear power system consisting mainly of thermal reactors with some small fraction of FBR. Unfortunately, the fuel breeding ratios (BR) in up-to-date thermal reactors are about 0.5 only. So, thermal reactors are not able to provide their own fuel self-sustainability. Some advance thermal reactors projects have been worked out, namely LWR with controlled neutron spectrum and LWR with super-critical pressure of coolant (SLWR), with BR values at the levels of 0.6-0.7 and 0.8-0.9, respectively. So, relatively small value should be added to BR of thermal reactors in order to reach typical BR values of FBR (BR ≥ 1). This small missing fuel additive can be produced in FNS blanket.

As is known, isotope $^{233}$U is able to form the better neutron balance in thermal reactor than $^{235}$U and plutonium can. Isotope $^{233}$U can be accumulated in thorium FNS blanket. Unfortunately, natural thorium, like rare-earth elements, is strongly dispersed in the nature, without rich Th-based ores and deposits. Till now, natural thorium is obtained as a by-product of the processes related with mining and extraction of other rare-earth elements, i.e. practically free of charge. Russian stockpiles of natural thorium are evaluated as 6000 tons [3], about two-year production level of natural uranium in Russia. Natural thorium can be used as a fertile material and converted to well-fissile isotope $^{233}$U in Th-blanket of FNS.

Let’s consider one version of natural thorium utilization with the following assumptions: only limited amounts (6000 t) of natural thorium may be used in Th-blanket of FNS; only small fraction (10%, i.e. 600 t) of natural thorium may be converted to fissile isotope $^{233}$U.

As is known, total electrical power of Russian nuclear power plants (NPP) in 2020 equals to about 30 GW(e). One thermal reactor of 1 GW(e) power burns-up one ton of fissile isotope annually and
accumulates one ton of fission products. Consequently, total demands of Russian NPP for $^{235}$U can constitute $\sim$30 t a year. Conclusion: the currently available stockpiles of natural thorium are large enough to supply all Russian NPP with $^{233}$U during 20 years even in open version of nuclear fuel cycle [4, 5]. In the case of closed nuclear fuel cycle with thermal reactors based NPP with BR about 0.5, the duration will be doubled, up to 40 years. If NPP on SCLWR with breeding ratios at the level of 0.8-0.9 will be put in operation in the nearest 25-35 years, then the duration elongates up to 100-200 years, historically significant time period. Consumption rate of natural thorium by one SCLWR will be at the level of 100-200 kg per GW(e)-year. So, only 3-6 tons of natural thorium must be mined annually for supply of Russian nuclear power which equals to $\sim$ 30 GW(e). If, according to the State Strategy [1], total power of Russian NPP will be tripled up to 90-100 GW(e), then total demands for natural thorium mining increases up to 9-18 tons per year, i.e. up to 0.3-0.6% from the level of natural uranium mining.

2. Selection of plasma composition for fusion neutron source
The following nuclear reactions can take place in thermonuclear D-D plasma:

\[
\begin{align*}
D + T & \rightarrow ^4\text{He} + n \ (14.1 \text{ MeV}) \\
D + ^3\text{He} & \rightarrow ^4\text{He} + p \\
D + D & \rightarrow 50\%: ^3\text{He} + n \ (2.5 \text{ MeV}) \\
D + D & \rightarrow 50\%: \text{T} + p \ (50\%)
\end{align*}
\]

Fusion of two deuterium nuclei can produce, with the same probability of 50%, either one neutron with 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) can, with high probability, enter to the concomitant thermonuclear reactions with deuterium nuclei. Probabilities of D-$^3$He and D-T reactions are larger than probability of D-D reaction by one and two orders of magnitude, respectively. Micro cross-sections of these three thermonuclear reactions are shown in figure 1 as the functions depended on energy of D, $^3$He and T relative movements. Micro cross-sections of $^{235}$U fission reaction as a function of neutron energy are presented in figure 1 too for comparison.

![Figure 1](image_url)

Figure 1. Micro cross-sections of $^{235}$U fission reaction as a function of neutron energy and micro cross-sections of three thermonuclear reactions of light nuclei as the functions depended on energy of D, $^3$He, T relative movements.
One basic D-D reaction and two concomitant reactions can produce, in average, 0.5 neutron (of 2.5 MeV energy) and 0.5 neutron (of 14.1 MeV energy). Plasma density is lower by seven orders of magnitude than typical densities of solid materials. Magnetic field, which is used for plasma confinement, is not able to retain uncharged neutrons. That is why thermonuclear neutrons can escape from plasma and from FNS with high probability. In the case of D-T plasma one D-T reaction results in emission of one high-energy (14.1 MeV) neutron.

It seems reasonable to use D-T plasma instead of D-D plasma because of the following two causes. Firstly, micro cross-sections of D-T reaction are larger by two orders of magnitude than micro cross-sections of D-D reactions. This means that it will be substantially easier to build-up thermonuclear reactor on D-T plasma and put it in operation. Secondly, 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 HTR blanket, one traditional well-fissile isotope $^{233}$U and two non-traditional but very promising isotopes $^{231}$Pa and $^{232}$U. As it can be seen from papers [6, 7], isotope $^{231}$Pa can stabilize neutron-multiplying properties of nuclear fuel (the higher fuel burn-up and the longer fuel lifetime, as a consequence), while isotope $^{232}$U can provide proliferation-protection of $^{233}$U-based fuel compositions.

When using D-T plasma, HTR operators must handle with radioactive tritium (tritium half-life is equal to 12.3 years). So, remote technologies for tritium management must be worked out and practically implemented. Tritium does not exist in the nature because of relatively short half-life. There is a possibility to produce significant tritium quantities by neutron irradiation of Li-containing materials in HTR through $^6$Li(n,α)T reaction.

Consumption of one tritium nucleus in $^6$Li(n,α)T reaction results in generation of one high-energy neutron. Generation of one new tritium nucleus in $^6$Li(n,α)T reaction consumes also one neutron. So, a wrong impression may appear that all thermonuclear neutrons must be consumed to reproduce tritium, and these neutrons could not be used to produce new fissile materials. In reality, high-energy thermonuclear neutrons can be intensely multiplied by threshold (n,2n) and (n,3n) reactions with multiplication factor of about 1.5. Reproduction of one tritium nucleus requires slightly above one neutron (roughly, 1.06 neutrons with accounting for reprocessing losses and short half-life of tritium). 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.

Breeding ratio of FBR reaches unity, i.e. excessive neutron amount in FBR is larger than that in HTR on D-T plasma by a factor of three. However, one excessive neutron in FBR is produced by fission reaction with energy release at the level of 200 MeV. One D-T reaction in HTR can emit only 0.3 excessive neutrons. Energy release of one D-T reaction equals to about 21 MeV (roughly, ten times lower) with accounting for γ-rays and radiative neutron capture in Th-blanket. If thermal powers of FBR and HTR are the same, then HTR on D-T plasma is able to produce the larger amount of fissile materials (by a factor of about 3) than FBR.

It is interesting to note here the following facts. Mean neutron energy in FBR is about 0.1 MeV. Mean neutron energy in spectrum of fission neutrons is about 2 MeV. Mean energy of spallation neutrons in accelerator-driven facilities covers the range from 1 MeV to 10 MeV. So, thermonuclear neutrons emitted by D-T plasma in HTR are characterized by the highest energy (14.1 MeV). The highest energy potential of thermonuclear neutrons is proposed to use for production of non-traditional isotope compositions containing $^{233}$U, $^{231}$Pa and $^{232}$U for introduction into fresh fuel of traditional thermal reactors. Scheme of main isotopic transformations which take place under neutron irradiation of Th-blanket is shown in figure 2.
As is seen, isotopes $^{231}$Pa and $^{232}$U are produced by threshold (n,2n) and (n,3n) reactions which can be initiated by high-energy neutrons only. Micro cross-sections of $^{232}$Th(n,f), $^{232}$Th(n,2n) and $^{232}$Th(n,3n) reactions are shown in figure 3 [8-10].

![Figure 3. Micro-cross-sections of fission, (n,2n) and (n,3n) reactions of $^{232}$Th.](image-url)

As is seen, threshold (n,2n) and (n,3n) reactions within high-energy range (above 7 MeV) can be initiated with the larger probability than fission reaction. This means that a possibility arises to produce non-traditional isotopes at low level of heat generation in Th-blanket. This circumstance can facilitate substantially development and implementation of HTR projects. Thus, just high-energy thermonuclear neutrons emitted by D-T plasma open a possibility of principle to produce non-traditional isotopes. As is known, $^{232}$Th is a threshold fissile isotope (figure 4). That is why slow neutrons will be mainly absorbed by $^{232}$Th with production of $^{233}$U after two relatively short $\beta$-decays (figure 2).
Micro cross-sections of neutron $^{232}$Th reactions within energy range from 0.01 eV to 14.1 MeV are shown in figure 4 [8-10]. As is seen, threshold (n,2n) and (n,3n) reactions will be dominant channels within the high-energy range (above 7 MeV). Within energy range from 2 MeV to 7 MeV main role goes to fission reaction, and within low energy range reaction of radiative neutron capture plays main role. Therefore, firstly, non-traditional isotopes $^{231}$Pa and $^{232}$U can be produced by only high-energy (7-14 MeV) neutrons. Secondly, fission reaction plays significant role only within rather narrow energy range (2-7 MeV). Fission reactions can occur with relatively low probability because fission cross-sections are at the level of decimal barn fractions, which are lower than cross-sections of threshold (n,2n), (n,3n) reactions and cross-sections of radiative neutron capture by one order of magnitude. As a result, heat generation rate in Th-blanket will be very small. Low-intensity heat generation can simplify requirements to thermal-technical equipment for heat utilization or removal. Thirdly, slow neutrons (with energy below 2 MeV) can be used to produce well-fissile isotope $^{233}$U, which is more advantageous nuclide than $^{235}$U for thermal reactors from the viewpoint of neutron economy.

3. Conclusion

If Th-blanket is used in HTR to produce fissile materials for nuclear power reactors, then available stockpiles of natural thorium are large enough to provide long-term (up to 20 years) operation of Russian NPP even on the open nuclear fuel cycle.

If SCLWR with breeding ratio at the level of 0.8-0.9 will be put in operation in the closed nuclear fuel cycle by the end of century, then demands for mining of natural thorium which is needed to supply Russian nuclear power system (three-fold electrical capacity) with fissile materials are equal to 0.3-0.6% from natural uranium mining.

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

The HTR on D-T plasma is able to produce the larger amounts of fissile materials (by a factor about 3) than FBR of the same thermal power.

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