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Advanced nuclear fuel cycle for the RF using actinides breeding in thorium blankets of fusion neutron source

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Abstract

The possible role of existing thorium reserves in the Russian Federation on engaging thorium in being currently closed (U-Pu)—fuel cycle of nuclear power of the country is considered. The application efficiency of thermonuclear neutron sources with thorium blanket for the economical use of existing thorium reserves is demonstrated.

The aim of the work is to find solutions of such major tasks as the reduction of both front-end and back-end of nuclear fuel cycle and an enhancing its protection against the uncontrolled proliferation of fissile materials by means of the smallest changes in the fuel cycle.

During implementation of the work we analyzed the results obtained earlier by the authors, brought new information on the number of thorium available in the Russian Federation and made further assessments.

On the basis of proposal on the inclusion of hybrid reactors with Th-blanket into the future nuclear power for the production of light uranium fraction $^{232\,+\,233+234}$U, and ^{231}Pa, we obtained the following results:

1 The fuel cycle will shift from fissile ^{235}U to ^{233}U which is more attractive for thermal power reactors.
2 The light uranium fraction is the most "protected" in the uranium component of fuel and mixed with regenerated uranium will in addition become a low enriched uranium fuel, that will weaken the problem of uncontrolled proliferation of fissile materials.
3 ^{231}Pa doping into the fuel stabilizes its multiplying properties that will allow us to implement long-term fuel residence time and eventually to increase the export potential of all nuclear power technologies.
4 The thorium reserves being near city Krasnoufimsk are large enough for operation of large-scale nuclear power of the Russian Federation of 70 GW (e.) capacity during more than a quarter century.

The general conclusion: the inclusion of a small number of hybrid reactors with Th-blanket into the future nuclear power will allow us substantially to solve its problems, as well as to increase its export potential.

Keywords: Hybrid “FUSION–FISSION” reactor with thorium blanket; Light uranium fraction; Protactinium-231; Multi-isotope uranium fuel; The stabilization of multiplication properties; The protection of fissile materials against uncontrolled proliferation.

Introduction

Closure of nuclear fuel cycle (NFC), the process under practical implementation now in the Russian Federation, can substantially upgrade efficiency of uranium utilization. Therefore, additional involvement of natural thorium resources into nuclear fuel cycle for further enlargement of practically unlimited natural uranium resources looks now as an option with the slightest validity. This option will require large additional expenses for development and industrial mastering of complicated technologies for thorium mining, primary processing, fabrication and handling with other nuclear fuel material. It would be appropriately to note here that till now no one country had decided yet to undertake wide involvement of natural

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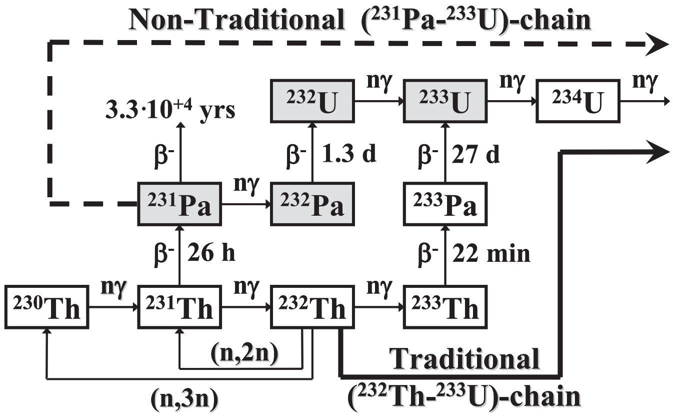

Fig. 1. Chains of nuclide transformations in the thorium–uranium fuel.

thorium resources into national nuclear power system (NPS), even India with large stockpiles of natural thorium.

So, involvement of thorium resources into NPS in the process of the NFC closure has to be validated by other and very weighty arguments. As is known, neutron-physical parameters of thermal power reactors can be remarkably improved by transition from uranium (^{235}U–^{238}U) fuel to uranium–thorium (^{233}U–^{232}Th) fuel. Just this consideration has been taken into account when "The Strategy on Development of Russian Nuclear Power System in the First Half of the XXI century" [1] was formed. The Strategy defines that closure of uranium–plutonium NFC will be followed by thorium involvement, and thermal reactors will be gradually transferred from uranium–plutonium fuel to uranium–thorium (^{233}U–^{232}Th) fuel.

Thorium application for generation of "light" uranium fraction

When the problem of thorium involvement into the NFC to be closed is under discussion, it seems reasonable to give attention to the following important (in a practical sense) circumstance. As is known, from the very beginning of nuclear power development and till nowadays the NPS is based on utilization of "heavy" uranium fraction $^{235+236+238}$U, where ^{236}U is a component of the regenerated uranium.

As far as thorium will be involved into the NFC, then a new (on its isotopic composition) uranium material appears in spent fuel, and the following neutron reactions (Fig. 1) are the channels for its generation:

(1) Radiative neutron capture by thorium with generation of fissile isotope ^{233}U.
(2) Threshold reactions of high-energy neutrons:

$$^{232}\mathrm{Th}(n,2n)^{231}\mathrm{Th}(\beta^-)^{231}\mathrm{Pa};\ ^{232}\mathrm{Th}(n,3n)^{230}\mathrm{Th}(n,\gamma)...^{231}\mathrm{Pa}.$$

(3) Radiative neutron capture by protactinium: $^{231}\mathrm{Pa}(n,\gamma)...^{232}\mathrm{U}$.

These reactions can generate, in addition to fissile uranium isotope ^{233}U, protactinium isotope ^{231}Pa and uranium isotope ^{232}U in the neutron-irradiated thorium. The chains of isotopic transitions initiated by neutron-thorium reactions can be grouped by such a way:

(1) "Traditional" chain that started from radiative neutron capture by ^{232}Th (the capture channel).

$$^{232}\mathrm{Th}(n,\gamma)^{233}\mathrm{Th}(\beta^-,T_{1/2}{=}22')^{233}\mathrm{Pa}(\beta^-,T_{1/2}{=}27\ \mathrm{d})\ ^{233}\mathrm{U}(n,\gamma)\ ^{234}\mathrm{U}(n,\gamma)\ldots$$

(1) "Non-traditional" chain that started from threshold $^{232}\mathrm{Th}(n,2n)$ and $^{232}\mathrm{Th}(n,3n)$ reactions (the threshold channel):

$$^{232}\mathrm{Th}(n,2n)^{231}\mathrm{Th}(\beta^-,T_{1/2}{=}26\ \mathrm{h})^{231}\mathrm{Pa}(n,\gamma)^{232}\mathrm{U}\ldots$$
$$^{232}\mathrm{Th}(n,3n)^{230}\mathrm{Th}(n,\gamma)^{231}\mathrm{Th}(\beta^-,T_{1/2}{=}26\ \mathrm{h})^{231}\mathrm{Pa}\ldots$$
$$^{231}\mathrm{Pa}(n,\gamma)^{232}\mathrm{Pa}(\beta^-,T_{1/2}{=}1.3\ \mathrm{d})^{232}\mathrm{U}(n,\gamma)^{233}\mathrm{U}(n,\gamma)\ ^{234}\mathrm{U}(n,\gamma)^{235}\mathrm{U}\ldots$$

So, introduction of natural thorium in fresh fuel composition will result in production of the "light" uranium fraction, namely mixture of light uranium isotopes ^{232}U, ^{233}U, ^{234}U with dominant role of well-fissile isotope ^{233}U.

If the "light" uranium fraction is used as a component of fresh nuclear fuel, then the NFC of nuclear power reactors (both thermal and fast reactors) may be based on utilization of either uranium-based fuel or mixed uranium–plutonium fuel compositions for a long time, even for an ultra-long time period taking into account practically unlimited resources of natural uranium and natural thorium. Besides, plutonium and minor actinides can be utilized within the frames of the NFC. Isotope composition of uranium fraction in fresh fuel will contain mixture of light uranium isotopes ^{232}U, ^{233}U, ^{234}U with uranium regenerated from spent LWR fuel.

If the "light" uranium fraction is generated by thorium-based fertile materials in relatively small number of highly efficient producers of fissile materials, then the main park of nuclear power reactors will be fueled by uranium as before. The hybrid thermonuclear "FUSION–FISSION" reactors with thorium blankets and with plasma parameters already achieved in contemporary experimental fusion installations can be regarded, in the first turn, as such producers. In the second turn, accelerator-driven facilities and fast reactors with thorium blankets can be also used to produce the "light" uranium fraction but they are characterized by relatively low production potential.

Thus, the closed (^{232}Th–^{233}U–^{235}U–^{238}U–Pu) NFC with multiple fuel recycle and with feeding by the "light" uranium fraction can form the closed (^{232}Th–^{232}U–^{233}U–^{234}U–^{235}U–^{236}U–^{238}U–Pu) NFC with multi-isotope (^{232}U–^{233}U–^{234}U–^{235}U–^{236}U–^{238}U) uranium fraction containing practically all uranium isotopes. As a consequence, the NFC "center of gravity" can be shifted from the currently used ^{235}U towards the use of ^{233}U in the future.

The "light" uranium fraction, in addition to content of very attractive fissile uranium isotope ^{233}U, can offer the following significant feature from nuclear non-proliferation point of