Possibility assessment for production of non-traditional nuclear fuel in thorium blanket of hybrid thermonuclear reactor

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Abstract. The paper aims at studying specific peculiarities in isotope composition of thorium blanket under irradiation by fusion neutron source (FNS) in hybrid thermonuclear reactor (HTR). High-energy (14 MeV) component of neutron spectrum in thorium HTR blanket results in production of non-traditional fissile mixture including not only $^{233}\text{U}$, but also $^{231}\text{Pa}$, $^{232}\text{U}$ and $^{234}\text{U}$. Extraction of such non-traditional fuel from spent Th-blanket and its utilization in traditional nuclear power reactors could increase fuel burn-up and strengthen regime of nuclear non-proliferation. The detailed investigations of these positive effects require high-precision neutron-physical analyses of thorium HTR blanket. The results obtained in these investigations are presented in the paper. The following results were obtained: the chosen model of HTR allowed us to form high-energy neutron spectrum in Th-blanket with significant fraction of 14 MeV neutrons; it was evaluated that threshold (n,2n) and (n,3n)-reactions are able to produce significant amounts of non-traditional target isotopes $^{231}\text{Pa}$ and $^{232}\text{U}$; it was shown that accumulation of non-traditional target isotopes weakened substantially in depth of Th-blanket. So, it seems reasonable to seek for optimal thickness of Th-blanket and, thus, to find optimal loading of natural thorium.

1. Model of fusion neutron source

High-energy (14 MeV) component of neutron spectrum in thorium HTR blanket results in production of non-traditional fissile mixture including not only $^{233}\text{U}$, but also $^{231}\text{Pa}$, $^{232}\text{U}$ and $^{234}\text{U}$. Extraction of such non-traditional fuel from spent Th-blanket and its utilization in traditional nuclear power reactors could increase fuel burn-up and strengthen regime of nuclear non-proliferation [1-4]. One-dimensional cylindrical HTR model [5] was used in numerical analyses. Radial HTR zones were presented as infinitely long axial layers. Equi-component D-T plasma ($n_T = n_D = 5 \cdot 10^{14} \text{ ion/cm}^3$) was considered as the main neutron source. Basic layout of the HTR model is shown in figure 1.
Thorium blanket was placed just beyond the first wall, i.e. high-energy 14 MeV neutrons could irradiate thorium and produce non-traditional nuclides via some threshold reactions. Before Th-blanket, fusion neutrons are partially moderated by the first wall. Thorium blanket is separated from the tritium reproduction zones (Li-containing zones) by structural materials. In order to intensify $^6\text{Li}(n,\alpha)^7\text{T}$ reaction, light-water layers are placed before, beyond and between the tritium reproduction zones. Those neutrons which came to the tritium reproduction zones have passed through Th-blanket. So, they are slow neutrons which are not able to initiate any threshold reactions. Thus, the tritium reproduction zones utilize slow neutrons coming from Th-blanket without decreasing production of non-traditional nuclides.

2. Neutron-physical analysis of thorium HTR blanket

Neutron-physical analyses of time-dependent evolution of isotope compositions in thorium HTR blanket were carried out with application of the Monte Carlo computer code SERPENT-2 [6-8] and continuous energy dependencies of evaluated nuclear data. Neutron load on the first wall was taken as 1 MW/m². This traditional value is estimated as an acceptable magnitude from the standpoint of the first wall strength properties.

2.1. The computer code SERPENT-2

The computer code SERPENT-2 is the multi-purpose code based on Monte Carlo methodology. SERPENT-2 applies continuous energy dependencies of evaluated micro cross-sections for solution of transport equations in three-dimensional geometry. The computer code SERPENT-2 has been initially created to solve the nuclear reactor physics problems. However, current SERPENT-2 capabilities are substantially wider than problems of the nuclear reactor physics. The SERPENT-2 applicability areas may be divided on the following three categories:

- Traditional problems of the nuclear reactor physics: spatial homogenization, determination of the reactor criticality, investigations of nuclear fuel cycle, simulation of nuclear research reactors and nuclear power reactors, validation of deterministic computer codes, and so on;
- Multi-physical simulations: neutron-physical computations in combination with thermal-hydraulic analyses, with CFD-code computations, with computations that take variations of fuel properties into account;
- Modelling of neutron and photon transport for determination of exposure dose, for solution of radiation shielding problems, for investigations in the areas of fusion reactors and medical physics.
In the process of computation, SERPENT-2 reads micro cross-sections with continuous energy dependencies from the evaluated nuclear data library in ACE format. Physics of neutron-nuclei interactions is based on classical kinematics of inter-particle collisions, on micro cross-sections from the evaluated nuclear data libraries in ENDF format and on the sampling from the probability table within the range of unresolved resonances. Nuclear data libraries in ACE format can take information from the evaluated nuclear data files JEF-2.2, JEFF-3.1, JEFF-3.1.1, ENDF/B-VI.8 and ENDF/B-VII. Information on radioactive decays and yields of fission products is taken from the standard evaluated nuclear data files in ENDF format.

2.2. Neutron spectrum in Th-blanket
The results obtained in calculation of neutron spectrum in Th-blanket are shown in figure 2. Two peaks are evidently seen: one peak in the vicinity of 10 MeV and another peak in the vicinity of 0.4 MeV. The first peak is directly caused by source of fusion neutrons while the second peak – by those neutrons which passed through the first wall, underwent inelastic scattering and lost significant fraction of their initial energy. Neutrons with resonance, epithermal and even thermal energies can be met in deep, inner layers of Th-blanket. Total fraction of these slow neutrons is substantially lower than fraction of high-energy neutrons. So, sufficiently high-energy neutron spectrum can be formed in Th-blanket even in the case of thick (10 cm) first wall. If thickness of Th-blanket decreases, then fraction of high-energy neutrons increases.

![Neutron spectrum in Th-blanket](image)

**Figure 2.** Neutron spectrum in Th-blanket.

2.3. Micro cross-sections and reaction rates in Th-blanket
This section of the paper considers basic characteristics which define efficiency of Th-blanket on production of main principal isotopes $^{231}$Pa and $^{232}$U, namely, micro cross-sections of $^{232}$Th and neutron flux in different radial zones of Th-blanket at the beginning of irradiation (figure 3). Since $^{232}$Th burn-up is relatively weak at technically mastered values of neutron load on the first wall (1 MW/m²), neutron reactions of $^{232}$Th must define neutron balance during full irradiation time.
As is seen, probability of radiative neutron capture increases with distance of neutron penetration into Th-blanket depth while probability of threshold (n,f), (n,2n) and (n,3n) reactions decreases. This effect is caused by gradual neutron slowing down. Micro cross-sections of radiative neutron capture by \(^{232}\)Th increase especially strongly in periphery of Th-blanket (in the last centimeters). At the same radial points neutron flux falls down approximately twice. So, it may be concluded that peripheral zones of Th-blanket are characterized by low efficiency on production of objective isotopes \(^{231}\)Pa and \(^{232}\)U. Production of these isotopes diminishes both in absolute values (kilograms per year) because of low neutron flux, and in relative values as compared with production of non-objective isotope \(^{233}\)U because of low ratios between micro cross-sections of threshold reactions and radiative neutron capture reaction. As a conclusion, optimization problem of the blanket thickness and thorium load in the blanket should be set and solved.

Cross-section of \(^{232}\)Th(n,f) reaction is nearly the same as micro cross-section of \(^{232}\)Th(n,3n) reaction, i.e. thorium fission reaction is weaker than reactions leading to production of isotopes \(^{231}\)U, \(^{231}\)Pa and \(^{232}\)U. This fact allowed us to expect insignificant heat generation rate in Th-blanket that simplifies heat removal from the blanket. Probably, it might be economically reasonable to throw this thermal energy down to the environment without its utilization.

The balance of energy-averaged reaction rates in Th-blanket is presented in figure 4. The shown processes include radiative neutron capture reaction of \(^{232}\)Th, fission reaction of \(^{232}\)Th, threshold \(^{232}\)Th(n,2n) and \(^{232}\)Th(n,3n) reactions, radiative neutron capture reactions of structural materials (Fe, Mo) and neutron leakage. Really, these reaction rates are appropriate micro cross-sections (see figure 3) multiplied on neutron flux and on concentrations of \(^{232}\)Th, Fe and Mo.
Neutron leakage rate is positive in the first 9 cm of the blanket and negative at longer distances in the blanket depth. This means that those neutrons, which came from plasma through the first wall and multiplied in the first 9 cm by threshold $^{232}$Th(n,f), $^{231}$Th(n,2n) and $^{230}$Th(n,3n) reactions, irradiate the next layers of the blanket.

The following conclusions may be made. Firstly, threshold $^{232}$Th(n,2n) and $^{232}$Th(n,3n) reactions, i.e. neutron reactions leading to production of objective isotopes $^{231}$Pa and $^{232}$U, play a remarkable role in the balance of neutron reactions. Nevertheless, main role in the balance is taken by $^{232}$Th(n,$\gamma$)$^{233}$U reaction. Secondly, $^{233}$U production rate in the blanket periphery is substantially higher than production rates of objective isotopes $^{231}$Pa and $^{232}$U. Therefore, more effective production of these isotopes may require reducing thickness of the blanket. Thirdly, rate of $^{232}$Th(n,f) reaction is low in all radial points of Th-blanket. This fact allows us to expect a real possibility for heat dumping in the environment without any utilization. Fourthly, neutron leakage rate plays a significant role in the neutron balance. Especially significant role is played by neutron leakage in the blanket depth.

2.4. Reaction rates in isotope transformation chain

This section of the paper analyses rates of neutron reactions which take place in isotope transformation chains of Th-blanket. Rates of radioactive decay, radiative neutron capture reaction and fission reaction are presented in table 1 for some short-lived isotopes.

| Isotope | Reaction | Micro cross-sections (b) | Neutron flux ($10^{14}$ n/(cm$^2$ s)) |
|---------|----------|--------------------------|---------------------------------------|
| $^{231}$Th | $\lambda$ | ($\sigma_{\gamma}$-$\phi$) | ($\sigma_{\beta}$-$\phi$) |
| $^{233}$Th | 0.64 | 0.000206 | 0.000045 | 0.000251 |
| $^{232}$Pa | 45.0 | 0.000174 | 0.000008 | 0.000182 |
| $^{233}$Pa | 0.53 | 0.000077 | 0.000230 | 0.000307 |
| $^{232}$Pa | 0.026 | 0.000125 | 0.000002 | 0.000127 |

As is seen, rates of radioactive decay are higher than rates of radiative neutron capture reaction by two orders of magnitude, at least. That is why the processes of radiative neutron capture and fission of these short-lived isotopes may be neglected at determination of isotope compositions produced in Th-blanket. If structural materials with upgraded radiation resistance will be used in the first wall, then neutron load (and neutron flux, as a consequence) can be increased, and difference of the reaction rates
can be decreased. However, elevation of neutron flux on several orders of magnitude is hardly probable.

Further, we compared the reaction rates related with different cross-sections, i.e. macro cross-sections multiplied on neutron flux. The same multiplier (neutron flux) was omitted, and relative masses of isotopes (kg per 1 t $^{232}$Th at the end of irradiation time).

Production rates of objective isotope $^{232}$U via threshold $^{232}$Th(n,2n)$^{231}$Pa(n,γ), $^{232}$Th(n,3n)$^{230}$Th(n,γ)$^{231}$Pa(n,γ) reactions and via $^{232}$Th(n,γ)$^{233}$U(n,2n) reaction were calculated. Contributions of threshold reactions to $^{231}$Pa (common isotope of both threshold reactions) are comparable with each other. Total rate of these threshold reactions was compared with rate of $^{231}$Pa(n,γ) reaction and rate of threshold $^{233}$U(n,2n) reaction. Micro cross-sections, relative masses and reaction rates at the end of irradiation time (1000 days) are presented in table 2.

### Table 2. Production rate of $^{232}$U via different channels.

| Reaction of $^{232}$Th | Evaluated reaction | Micro cross-section, barn | Relative mass, kg/t | Reaction rate, barn∙kg |
|------------------------|--------------------|---------------------------|---------------------|------------------------|
| (n,2n)                 | $^{232}$Th(n,2n)   | 0.082                     | 988.6               | 80.9                   |
| (n,3n)                 | $^{230}$Th(n,γ)   | 3.679                     | 0.911               | 3.35                   |
| (n,2n)+(n,3n)          | $^{231}$Pa(n,γ)   | 6.167                     | 2.564               | 15.81                  |
| (n,γ)                  | $^{233}$U(n,2n)   | 0.010                     | 6.188               | 0.063                  |

As is seen, total rate of threshold reactions is large than rate of $^{232}$Th(n,γ)$^{233}$U(n,2n) reaction by above two orders of magnitude. Rate of $^{232}$Th(n,2n) reaction is 24 times larger than rate of $^{232}$Th(n,3n) reaction. So, the lion’s share of $^{232}$U is produced via $^{232}$Th(n,2n) reaction. Contributions of all other reactions are negligibly small.

Some parameters of heat generation rate at the end of irradiation time are presented in table 3. As is seen, main contributor is isotope $^{233}$U while contribution of $^{232}$Th is lower by two orders of magnitude. Taking into account the fact that $^{232}$Th is a threshold-fissionable isotope, and Th-blanket contains 99.86% $^{232}$Th, it may be concluded that total heat generation rate at the end of irradiation time remains insignificant. Therefore, heat removal does not represent a complicated problem, and thermal energy may be thrown down to the environment without any utilization.

### Table 3. Rates of fission reaction for some relevant isotopes at the end of irradiation time (1000 days).

| Isotope | Micro cross-section, barn | Relative mass, kg/t | Fission rate, barn∙kg | Isotope |
|---------|--------------------------|--------------------|----------------------|---------|
| $^{232}$Th | 0.025       | 998.6              | 25.26                | $^{232}$Th |
| $^{230}$Th | 0.057       | 0.911              | 0.052                | $^{230}$Th |
| $^{231}$Pa | 0.256       | 2.564              | 0.656                | $^{231}$Pa |
| $^{232}$U | 3.429       | 0.089              | 0.305                | $^{232}$U |
| $^{233}$U | 7.477       | 6.188              | 46.27                | $^{233}$U |
| $^{234}$U | 0.455       | 0.072              | 0.033                | $^{234}$U |

Thus, it can be concluded that short-lived isotopes may not be taken into consideration, their contributions are negligibly small. Only threshold $^{232}$Th(n,2n) reaction of all other threshold reactions should be taken into account.

2.5. Thorium burn-up

Time-dependent thorium burn-up via different channels (radiative neutron capture, fission, threshold (n,2n) and (n,3n) reactions) is shown in figure 5.
Naturally, all time dependencies are linear functions because rates of all channels are linear functions of neutron flux and neutron spectrum. Neutron flux is defined by fixed FNS intensity according to neutron load on the first wall (1 MW/m²). Time-dependent variations of neutron spectrum are very small because of low thorium burn-up and low accumulation of new isotopes. By the end of irradiation time, only about 10 kg $^{232}$Th was incinerated per initial one ton of $^{232}$Th, i.e. thorium burn-up is nearly 1% HM. Mean fuel burn-up in current light-water reactors of VVER-1000 type comes nearer to 5% HM while maximal fuel burn-up – to 7% HM. The ways towards intensification of thorium burn-up and production of objective isotopes must include the attempts to provide higher values of neutron load on the first HTR wall and longer irradiation time of Th-blanket. Anyway, it is necessary to seek for new structural materials with upgraded radiation resistance.

As is expected, $^{232}$Th(n,γ) reaction is a main channel of thorium burn-up. However, threshold $^{232}$Th(n,2n) channel is not negligibly weak, and slightly more intense than $^{232}$Th(n,f) channel. These results allowed us to expect intense production of traditional isotope $^{233}$U and non-traditional objective isotopes $^{231}$Pa and $^{232}$U.

2.6. Production of isotopes $^{233}$U, $^{231}$Pa and $^{232}$U
Production of some isotopes in Th-blanket under irradiation by FNS is shown in figure 6 as a function of irradiation time.
as expected, the largest fraction of isotope $^{232}$U and $^{233}$Pa is presented in figure 6 because $^{233}$Pa rapidly decays into $^{233}$U (half-life $T_{1/2} = 27$ days). So, rate of $^{233}$Pa radioactive decay is much higher than rates of its radiative neutron capture and fission. As was expected, the largest fraction of isotope $^{233}$U is produced via radiative neutron capture of $^{232}$Th followed by two rapid $\beta$-decays of isotopes $^{233}$Th and $^{233}$Pa. However, production of objective isotope $^{231}$Pa via threshold $^{232}$Th(n,2n) reaction constitutes a remarkable part of $^{233}$U production. Production of the next isotopes $^{232}$U via $^{231}$Pa(n,$\gamma$) reaction and $^{234}$U via $^{233}$U(n,$\gamma$) reaction is, of course, substantially less.

2.7. Isotope composition of the produced uranium

Contents of uranium isotopes $^{232}$U and $^{234}$U in the uranium produced in Th-blanket are shown in figure 7 as functions of irradiation time.

As is seen, contents of uranium isotopes $^{232}$U and $^{234}$U increase nearly in a liner manner. At the end of irradiation time (1000 days) these contents reach the values of 1.6% and 1%, respectively. The
remaining content (97.4%) is occupied by isotope $^{233}$U. In fact, highly-enriched weapon-grade uranium is produced in the irradiated Th-blanket. Such effective fuel for nuclear power reactors requires strict control from the standpoint of nuclear weapons non-proliferation. Production and management of this weapon-grade uranium must be strictly controlled by the IAEA inspectorate. The produced weapon-grade uranium may be diluted by natural or depleted uranium down to necessary content of fissile isotope $^{233}$U. In addition, such a dilution can provide proliferation resistance of the produced uranium at the highest isotopic level. In this case, main fissile isotope $^{233}$U will be surrounded by the lighter isotope $^{232}$U and by the heavier isotopes $^{234}$U and $^{238}$U.

The following question arises: are contents of uranium isotopes $^{232}$U and $^{234}$U (1.6% and 1%, respectively) in the produced uranium large or small? Numerical evaluations showed that so small contents of these isotopes are not able to influence substantially on neutron-physical properties of nuclear fuel because the produced uranium will be diluted by isotope $^{238}$U. If the produced uranium is diluted by natural or depleted uranium down to 5%, $^{233}$U, then contents of uranium isotopes $^{232}$U and $^{234}$U are reduced by $\sim 25$ times down to 0.065% and 0.04%, respectively. These values are negligibly small.

Presently, the glove-box technology is used to fabricate fresh nuclear fuel for light-water reactors from the reprocessed uranium. According to the Russian technical regulations, $^{234}$U content in reactor-grade uranium must be below 0.2%. So strict restriction is caused by intense $\alpha$-activity of isotope $^{234}$U ($T_{1/2} = 2.45 \times 10^7$ years). If uranium is being enriched with application of gas-diffusion or gas-centrifuge technology, then $\alpha$-particles emitted by $^{234}$U are able to disorder the enriching process by chemical dissociation of uranium hexafluoride $\text{UF}_6$ molecules with generation of free fluorine and lower uranium fluorides (mainly, $\text{UF}_5$ and $\text{UF}_4$). The presence of these lower uranium fluorides with small volatility can disturb the uranium enriching process. The low-volatile uranium fluorides can precipitate on inner surfaces of technological units (centrifuges, pipelines) while free fluorine can act as a strong corrosion-aggressive element.

As for isotope $^{232}$U, the Russian technical regulations require that $^{232}$U content in uranium must be below $2 \times 10^{-5}$. So strict restriction is caused by the same reasons that those in the case of $^{234}$U. However, these reasons are substantially stronger because of the following facts. Half-life of $^{232}$U is significantly shorter than that of $^{234}$U (69 years versus $2.45 \times 10^7$ years). Decay chain of $^{232}$U includes five additional $\alpha$-emitters. Besides, one member of $^{232}$U decay chain, namely isotope $^{208}$Tl, is a source of high-energy (2.6 MeV) gamma-rays. At the end of irradiation time (1000 days), $^{232}$U content in the produced uranium is $\sim 10^7$ times larger than the acceptable value for the glove-box technology of U-based fuel fabrication. Even if the produced uranium is diluted by isotope $^{238}$U, then $^{232}$U content exceeds the acceptable value ($2 \times 10^{-5}$) by $\sim 10^5$ times, at least. This means that remote technologies should be developed for nuclear fuel fabrication from uranium with such isotopic composition. Intense emission of high-energy gamma-rays can act as a serious barrier against any ways towards the use of this uranium by terrorists. If this barrier is overcome by terrorists for manufacturing of a nuclear explosive device (NED), they are enforced to carry out preliminary uranium enriching with isotope $^{235}$U in cascade of gas-centrifuges, for instance. If so, high $\alpha$-activity of $^{235}$U and its decay products can provoke chemical dissociation of $\text{UF}_6$ molecules. As it can be seen from comparison with natural uranium enriching, elevation of $^{235}$U content, when $^{233}$U is surrounded with the lighter and heavier uranium isotopes $^{232}$U, $^{234}$U and $^{238}$U, is much more complicated technological problem. Solution of this problem will require forming a special enriching cascade or two separate cascades for extraction, at first, the heavier isotopes and then extraction of the lighter isotopes. Besides, difference of $^{232}$U, $^{233}$U and $^{234}$U atomic weights is equal to 1 Da only while that in the process of natural uranium enriching equals to 3 Da. So small difference can complicate additionally the uranium enriching process and reduce efficiency of the process. If terrorists will try to manufacture NED without isotope separation extraction of $^{235}$U, then intense heat generation by $^{235}$U can melt down chemical explosive, and NED will be disabled. Intense neutron emission by $^{232}$U from spontaneous fission reactions can lead to the premature initiation of chain fission reaction in NED and reduce drastically energy yield of nuclear
explosion. Thus, large $^{232}\text{U}$ content is an extremely strong barrier against any unauthorized usage of the produced $^{233}\text{U}$.

Technical capabilities of the state-level industrial enterprises are evidently larger than those of any terrorist organization. That is why we can always define such a value of $^{232}\text{U}$ content in uranium which allows the state-level enterprises to work with this uranium but disallows terrorists to do the same.

2.8. Production of $^{231}\text{Pa}$

Ratio of $^{231}\text{Pa}$-to-uranium content in Th-blanket is shown in figure 8 as a function of irradiation time.

![Figure 8](image)

**Figure 8.** Ratio of $^{231}\text{Pa}$-to-uranium content as a function of irradiation time.

As is seen, ratio of $^{231}\text{Pa}$-to-U content is practically time-independent value (about 0.38). This means that, if uranium is enriched up to 5% $^{233}\text{U}$, then uranium fuel contains 1.9% $^{231}\text{Pa}$. As is known, micro cross-section of radiative neutron capture by $^{231}\text{Pa}$ within thermal energy range is higher than that of $^{238}\text{U}$ on nearly 75 times. So intense neutron capture by $^{231}\text{Pa}$ is able to produce beneficial effect on neutron balance and stabilize neutron-multiplying properties of such a fuel at its energy utilization in nuclear power reactors.

2.9. Fraction of high-energy neutrons in Th-blanket

Since objective isotopes $^{231}\text{Pa}$ and $^{232}\text{U}$ are produced by threshold (n,2n) and (n,3n) reactions, it is interesting to study radial distribution of high-energy neutrons in Th-blanket. Only these high-energy neutrons are able to initiate threshold (n,2n) and (n,3n) reactions. As it was shown in figure 5, neutron spectrum does not change remarkably during full irradiation time because of low $^{232}\text{Th}$ burn-up (only about 1.1% HM). That is why radial distribution of high-energy neutrons in Th-blanket is presented in figure 9 for the beginning of irradiation time.
As is seen, fraction of high-energy (E > 6.5 MeV) neutrons decreases from the front edge of Th-blanket (plasma-blanket border) to the back edge (blanket-structure border) approximately twice. Radial degradation of high-energy neutron flux is explained by gradual neutron slowing down in elastic and inelastic collisions. Basing on this dependency, it may be concluded that all relevant isotopes, including objective isotopes, will be accumulated in Th-blanket in non-uniform spatial manner. This conclusion is confirmed by numerical results presented below.

2.10. Production of isotopes in Th-blanket
Radial distributions of isotopes production in Th-blanket are shown in figure 10.

As is seen, production of objective isotopes $^{231}$Pa and $^{230}$Th, which can be generated only by high-energy neutrons via threshold (n,2n) and (n,3n) reactions, is substantially more intense at the front edge as compared with that at the back edge of Th-blanket (approximately by 6 times). This can be
explained by softening of neutron spectrum (see figure 9), i.e. by slowing of high-energy neutrons down to the energy range $E < 6.5$ MeV. Production of traditional isotope $^{233}$U, at first, decreases and then begins increasing. Probably, such radial distribution of $^{233}$U production may be explained by the following reason. The moderated neutrons come to the energy range with low micro cross-sections of $^{232}$Th$(n,\gamma)^{233}$U reaction (from 1 eV to 100 eV). However, this effect requires further investigations.

Production of isotopes $^{232}$U and $^{234}$U is so small that their radial distributions are almost indistinguishable in figure 10. These radial distributions are separately considered in the next section.

2.11. Radial distribution of uranium isotope composition in Th-blanket

Radial distributions of uranium isotopes ($^{232}$U and $^{234}$U) production in Th-blanket are presented in figure 11.

![Figure 11. Uranium isotope composition in Th-blanket.](image)

Minimal production of isotope $^{232}$U in the middle of Th-blanket is explained by softening of neutron spectrum. However, production of isotope $^{233}$U begins increasing in peripheral layers of Th-blanket. This effect can be explained by intense production of isotope $^{233}$U in the blanket periphery (see figure 10) and by initiation of threshold $^{231}$U$(n,2n)^{232}$U reaction. Production of isotope $^{234}$U increases substantially in the vicinity of the blanket back edge. This effect can be also explained by intense production of $^{233}$U and initiation of $^{233}$U$(n,\gamma)^{234}$U reaction.

3. Comparison with other calculations

Production of various isotopes in Th-blanket of HTR on D-T plasma has been also investigated in papers [9, 10]. Experimental and computational data on reaction rates per one fusion neutron ($E = 14$ MeV) are presented in table 4. These results demonstrated sufficiently good agreement.

| $^{232}$Th reactions | Experiment [9] | Calculation [10] |
|----------------------|----------------|------------------|
| $(n,\gamma)$         | 1.63 ± 0.10    | 1.58             |
| $(n,2n)$             | 0.42 ± 0.04    | 0.58             |
| $(n,3n)$             | 0.30 ± 0.05    | 0.15             |
| $(n,f)$              | 0.17 ± 0.01    | 0.19             |
| Leakage              | 0.78 ± 0.04    | 0.76             |
Time-dependent variations of isotope compositions produced in thorium HTR blanket are shown in figure 12 [10]. Good qualitative agreement can be observed between the results published in [10] and the results presented in the paper. Small discrepancies may be explained by different models of hybrid thermonuclear reactor and HTR blanket, by application of different evaluated nuclear data files and by numerical approximations.

![Figure 12. Isotope composition of Th-blanket as a function of irradiation time.](image)

4. Conclusions
The following results are presented in the paper:

- The proposed model of fusion neutron source makes it possible to form sufficiently high-energy neutron spectrum in Th-blanket with remarkable fraction of 14 MeV neutrons;
- It was demonstrated that production of non-traditional objective isotopes $^{231}\text{Pa}$ and $^{232}\text{U}$ in significant quantities is possible via threshold ($n,2n$) and ($n,3n$) reactions;
- A possibility was shown to use simplified chain of isotope transformations without taking short-lived isotopes into consideration. Only one $^{232}\text{Th}(n,2n)$ reaction must be accounted for;
- It was shown that production of objective isotopes in Th-blanket depth reduced substantially. Therefore, it seems reasonable to find optimal thickness of Th-blanket and, as a consequence, optimal mass of thorium loading.

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