Nonproliferation Problem in (U-Pu) and (Th-U) Closed Fuel Cycles

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Introduction

At the **Millennium Summit** the President of the Russian Federation put forward the initiative related to ensuring energy supply for sustainable development of mankind, cardinal solution of nuclear weapons’ non-proliferation problem and environmental remediation of the Earth. He proposed to establish an international project under the auspices of the IAEA, targeted at solving the key problems of nuclear power. The Russian President’s initiative is a political step based on critical analysis of the state of the world power industry.

This initiative was considered and approved by the Scientific Council of the Russian Research Center «Kurchatov Institute». This resulted in preparing several proposals, which could become the basis of some specific innovative projects in nuclear technology field. These proposals were prepared for consideration of the international expert group within the framework of the **IAEA** project.

The power development in the regions of the world is likely to differ essentially by rate and structure (both of fuel and industry). Without a general concept of power development, and in conditions of rapid globalization of energy markets, the task of ensuring sustainable power development will be constantly and considerably impeded.

Solution of mankind’s power problems would require a significant increase of nuclear share in energy production, which is impossible without improvement and development of the nuclear fuel cycle, without involving new kinds of nuclear fuel into nuclear power industry, and without developing nuclear power installations of various types and capacities with thermal and fast neutrons reactors.

Many necessary elements of the future nuclear power structure have been sufficiently developed. However, much is still to be done in order to create an integral structure of nuclear power capable of long-term and large-scale development. In the first place this concerns the development of fuel cycle technologies, elements and structure and the solution of the radwaste management problem.

Development of the new, more up-to-date nuclear power technologies, fully using the lessons of half a century experience and satisfying the conditions of the large-scale power industry, requires great intellectual and financial efforts and active joint activities of all the countries interested in nuclear power development and, first of all, of those which possess research and engineering potential and experience.

The goal of the International Project may become the development and implementation of separate innovative projects of some specific systems and technologies of nuclear fuel cycle and nuclear power facilities based of agreed positions and requirements.

1. Proposals on the International Project’s General Contents and Composition

1.1. Requirements to the Future Nuclear Power

Nuclear power should ensure the possibility of an economically effective, reliable and safe energy production in all regions of the world, where the fossil fueled power development is in principle impeded because of their economic, resource and environmental limitations, which restrict the development of these regions.

Meeting essentially more strict safety, environmental acceptability and non-proliferation requirements compared with those for fossil fueled power industry, today the nuclear power already takes into account the external expenses of various kinds which up to now almost haven’t been taken into consideration in the field of fossil fueled industry. Accounting of these external expenses would result in a substantial growth of price for the energy derived from fossil fuels. Nuclear power helps the mankind to reduce the fossil fuels consumption and the volume of the releases into the environment, to slow down the growth of energy costs while continuing the large-scale power industry development, and to extend the period when the use of market relations peculiar to the modern economic mechanism would still be acceptable.

One of the main tasks in transition to the sustainable development is to find economic and political stimulating moments enabling to research and develop:

- elements and structures of the nuclear fuel cycle with expanded fuel breeding;
- reactors capable of meeting various demands of population in various regions of the world.

The main direction of the first-stage research is to establish a substantiated set of the requirements for the long-term and large-scale development of nuclear power in the fields of:

- economic competitiveness;
- required level of fuel breeding;

- radiation and nuclear safety of population and environment and safe radwaste disposal, including decommissioning of various nuclear power objects;
- acceptability from the point of view of nuclear technologies' and materials' non-proliferation.

1.2. Optimum Structure and Main Elements of the Future Nuclear Power

It would be necessary to choose the nuclear power structure, which would meet various requirements, include the closed **U-Pu** and **Th-U** fuel cycles with optimum neutron and nuclide balance, provide for the required nuclear fuel production and for multiple fuel recycling, minimize the quantity of radwaste and ensure the possibility to use valuable products.

The main research directions are as follows:

- closed uranium-plutonium and thorium-uranium fuel cycles with expanded nuclear fuel breeding at the first stage of large-scale development, conventional breeding at the stage of its regular application and elimination of nuclear fuel and radwaste at the closing stage of nuclear power development;
- scientific and technical substantiation and recommendations concerning the power reactors of various destination and capacity:
    - fast breeder reactors: required level of fuel breeding and base load energy production;
    - thermal reactors: electricity and heat production, technological applications, transport facilities with largely varying capacities and modes;
    - special reactors for burning actinoids and production (transmutation) of required radionuclides.

1.3. Solution of Nuclear Non-Proliferation Problems

The first nuclear weapon was obtained in the absence of nuclear power. That is why the nuclear power does not completely deserve the hallmark of nuclear weapons «proliferator». The way from nuclear power to nuclear weapons is much more complicated, since it is much more difficult to implement a controlled release of energy than an uncontrolled one [2]. Nevertheless, the increase of the volumes of nuclear energy use, utilization of weapon-grade materials, expansion of their application fields, enlarging the number of countries using nuclear energy, nuclear fuel breeding, closing of the fuel cycle and progress of nuclear technologies objectively contain the danger of nuclear proliferation. Therefore, it is necessary to take a number of additional measures directed at reinforcement and improvement of nuclear non-proliferation system.

The efforts to reduce the risk of nuclear proliferation should comprise the following directions:

- control of proliferation-sensible technologies;
- choice of strategic solutions and technical means at all the fuel cycle links with a view to reduce the accumulation of weapon-grade nuclear materials, reduction of their total volume and circulation fluxes;
- utilization of the excess weapon-grade nuclear materials;
- development and implementation of the technologies of nuclear materials' management, which would ensure the nuclear materials' internal protection, i. e. use the technological barriers preventing from the unauthorized removal of nuclear materials from the cycle;
- improvement of the organizing measures and technical instruments of physical protection and nuclear materials control on the basis of the non-proliferation risk quantitative analysis (safety probabilistic analysis analogue).

With account of the steadily growing education level in the world community, the scientific and technical progress in the field of information and knowledge dissemination systems, permanent attention would be required to the restriction of the unauthorized dissemination of the information on the technologies of nuclear weapon-grade materials' production.

2. Tasks and Expected Results of the Project

While working out the international recommendations for the large-scale nuclear power development it would be necessary to choose the optimum development trajectory, from today's state till far into the future. Here the necessity of joint development and demonstration, in the nearest future, of the nuclear technologies, which will become the basis of the following wide-scale development, may appear. These technologies must be aimed at solving such problems as:

- practically unlimited availability of the fuel resources due to efficient use of natural uranium, and, later, thorium;
- elimination of the severe accidents with radiation releases, requiring evacuation of the population, under any equipment failures, personnel errors and external effects, mainly owing to the inherent properties of the nuclear reactors and their components and their conformity to natural laws;
- safe energy production and waste utilization with the minimum impact on the environment due to closing the fuel cycle with burning of long-lived actinides and fission products in the reactor and to reliable disposal of radwaste;
- maximum closing of nuclear weapons proliferation channel connected with nuclear power industry and ensuring of reliable nuclear fuel protection from an unauthorized use;

- economic competitiveness and attractiveness due to the low cost and the necessary level of fuel breeding, high efficiency of the thermodynamic cycle, solution of **NPP** safety problems without complication of their constructions and without any extreme requirements for the equipment and the personnel.

Some of these problems could be solved in course of implementation of the specific proposals related to innovative reactor type, which are given below. As a result of the joint work on the particular projects the recommendations could be worked out for:

- fuel cycle technologies and enterprises, such as storage, transportation, spent nuclear fuel and radwaste reprocessing, radionuclide separation and radwaste disposal;
- advanced fast neutron reactors of large and medium capacity, thermal neutron reactors of large, medium and low capacity with various designations;
- liquid fuel reactors as elements of the nuclear fuel cycle, used both for burning and transmutation of separate nuclides, and as energy technology reactors, including provision of energy supply;
- choice and improvement of the ways of nuclear power transition to large-scale energy production.

Also proposed were the methods of permanent analysis and the ways of step-by-step solution of the existing and arising problems in nuclear power field.

3. Nuclear Weapon Non-Proliferation Problems

On the Nuclear Weapon Non-Proliferation Agreement coming into force on March 5, 1970, the nuclear weapon non-proliferation regime began to form. By now the regime has taken the form of a vast comprehensive complex comprising political, juridical, organizing and scientific-technical measures which are implemented both in the frames of the international organizations, and on the various multilateral or bilateral levels.

However, it should be mentioned that the main «instruments» of the nuclear weapon non-proliferation regime currently existing were ideologically and technically formed in the end of 1960-s and in the beginning of 1970-s. Hence, they reflect as a whole the political situation of that time, the proliferation danger level corresponding to that time situation and to the economic and technical possibilities available at that time of the most developed but not possessing the nuclear weapon countries to create or to obtain the nuclear weapons.

At that period the nuclear countries were actively increasing their reserves and perfecting their nuclear weapon. They were just proceeding to the nuclear power development and to the development of the civil nuclear industry. There was practically no nuclear power in any appreciable scale in the countries not possessing the nuclear weapon.

During the past years, firstly, the gradual changes in the political and economic situations occurred and, secondly, the significant scientific and technical progress was achieved in the field of the nuclear engineering and technology. The development of the world nuclear power and industry resulted in the nuclear materials considerable accumulation in various countries. There appeared a great number of specialists in the field of the nuclear engineering and technology all over the world. The international sharing the scientific and technical information in the field of the nuclear engineering and technology became widely spread. Much special knowledge dealing with the creation of the nuclear weapon systems, though simple they be, were no longer secret. This all essentially influences the effectiveness of the existing regime of the nuclear weapon non-proliferation and requires the development of the new approaches to its implementation.

In our opinion the current political situation in the field of the nuclear weapon non-proliferation is mainly characterized by the following:

a number of countries have not as yet joined the Nuclear Weapon Non-Proliferation Agreement. A group of the so called «threshold» countries belongs to them. Nowadays it is difficult to answer exactly the question of how many of the «threshold» countries there are; the known political ambitions of a number of countries-participants of the Non-Proliferation Agreement also reveal their aspiration to get the nuclear weapon; wide spread of the international terrorism practice.

It is obvious that the task of the nuclear weapon non-proliferation understood as the task of restricting the number of the countries possessing the nuclear weapons is, beyond all doubt, the political task and it can be solved only by the political means, first of all, by the elimination of the countries' motivation to get the nuclear weapon.

Nevertheless, there is a wide area for the activity of the substantiation, adoption and implementation of the scientific and technical solutions aimed at the timely revelation of the nuclear weapon proliferation threat, to hamper and to detain its implementation and, thereby, to provide the necessary time margin to eliminate the threat by the political means.

As for the prevention from the possibility of getting the nuclear weapon by some subnational or independent terrorists groups, the solution of this problem can be achieved, first of all, by the technical means.

The elaboration of the technical and organizing measures aimed at the decrease of the risk of the nuclear weapon proliferation should become an important and indispensable part of the International Project. The basis of such an elaboration can be only the profound analysis both of the nuclear power development general concept, and of the application of the specific technological solutions, including the choice of the reactor systems and the nuclear fuel cycle arrangement schemes.

As a result, the recommendations should be formulated on controlling the technologies vulnerable from the view point of the signs of the nuclear weapon proliferation risk. The strategic solutions and the technical means should be chosen in all the component parts of the nuclear fuel cycle with the aim to diminish the accumulation of the nuclear materials appropriate for the nuclear weapon fabrication, to decrease their general amounts and the circulation flows, as well as with the aim to facilitate the application and the increase of the effectiveness of the international control measures and to provide the necessary and sufficient transparency of the nuclear activity from the view point of the non-proliferation regime.

The measures for the prevention of the nuclear weapon proliferation are international in essence, therefore they ought to be worked out and applied in close international cooperation so that they were politically and technically acceptable for all the countries interested in the consolidation of the non-proliferation regime.

The International Project Organization is to provide the conditions for the long cooperative work of the scientists and the engineering experts from the countries interested in the non-proliferation field problems.

The permanent scientific and technical cooperation in this field will make it possible:

- to arrive at the full mutual understanding between the scientists and the engineering experts of the countries involved;
- jointly to assess the effectiveness of the available engineering solutions;
- to work out the new mutually acceptable engineering solutions and to estimate them both from the view point of their effectiveness, and their acceptability, taking into consideration the national safety;
- to demonstrate before the influential circles adopting the political decisions all the available technical facilities;
- to coordinate the technical policy of the countries concerned on the international arena, including in discussing the problems dealing with the enlargement of the functions and with increasing the effectiveness of the IAEA international guarantees.

Among the long-term tasks of the scientific and technical cooperation of the countries interested in the non-proliferation problems the following must be present:

- export control of the nuclear materials and of the double purpose objects;
- possibility of the exposure and monitoring of the undeclared nuclear activity;

- development of the supporting facilities for the national and international programs of the nuclear weapon non-proliferation;
- wide scale international programs of the scientific and technological cooperation for diminishing the proliferation risk;
- profound systems analysis of the current and future condition and of the effectiveness of the non-proliferation regime.

During the past period many international, multilateral, bilateral and other agreements were concluded in the sphere of the nuclear weapon non-proliferation regime and in the nuclear weapons restriction.

The development of this process was evolutionary and many agreements and treaties were concluded without the mutual scientific and technical coordination with each other. There are many of them and many are to be concluded in the nearest or not far off future.

The international and other organizations dealing with the nuclear weapons restriction and with the nuclear weapon non-proliferation regime grow in the number and the dimensions and their financial provision becomes increasingly expensive.

It is time to analyze in a complex and comprehensive way all the treaties and agreements, the international organizations regulatory mechanisms in the field of the nuclear weapon non-proliferation regime and the nuclear weapons restriction with the goal to elaborate the further approaches to their development and the recommendations for their optimization as of a whole complex.

It should be pointed out that by now in various countries much research work has been done to study the nuclear power fuel cycles properties the use of which permits to withstand the nuclear weapon proliferation. The goal of such studies is to assess the potential possibilities of the various fuel cycles to reduce the proliferation risk while developing further the peaceful nuclear power. It is meant that by modifying the existing nuclear fuel cycles and by implementing some new ones, the proliferation risk will be reduced in some countries possessing the programs of the peaceful use of the nuclear power but not having the full trust of the international community with respect to the non-proliferation problem.

The systematization, assessment and the further development of such jobs should become one of the tasks of the International Project.

However, in the modern conditions among the problems related with the nuclear weapon non-proliferation and with the increase of the nuclear power fuel cycles protection one of the most important but little studied problems is the problem of the assessment of the nuclear terrorism risk related with the criminal groups activity, including the international ones. Such groups, some of them being connected with the state power system, can act outside the frames of the nuclear power application programs but they use these programs for the achievement of their own purposes, including such as: fabrication of the nuclear weapon and the execution of the nuclear terrorism.

The preliminary investigations of this problem made at the «Kurchatov Institute» show that taking into account the terrorists groups possibilities, the danger of various nuclear materials and technologies from the view point of the risk of the nuclear weapon concealed fabrication should be assessed by the criteria different from those used usually in the assessment of the non-proliferation measures effectiveness. The investigations of such kind and the elaboration on their basis of the recommendations on the nuclear materials treatment and on the nuclear technologies use should also be included into the tasks of the International Project.

4. Features of development of (U-Pu) and (Th-U) fuel cycles

Development of thorium fuel cycle can be greater if the nuclear power were not a lateral product of the war industry aimed at fastest creation of nuclear bomb. Uranium has one main advantage over thorium - natural uranium contains (although in minor amounts) isotope ^{235}U which is fissile when absorbing neutrons. When uranium is used as a fuel in nuclear reactors, self-sustaining reaction of fission of ^{235}U nuclides can be achieved. Besides, excess neutrons in such nuclear cycle allows for their use for convertion of ^{238}U in ^{239}Pu which is the most effective explosive material for nuclear bombs for production of which the nuclear power was developed. Besides, for creation of nuclear bombs giant industrial enrichment facilities were created, technological processes were developed which later appeared rather acceptable from economic viewpoint for production of uranium fuel for power reactors.

This fact determined in the majority of countries (USA, Canada, West-Europe countries, Japan) that national nuclear programs were developed on the basis of U-Pu fuel cycle. Currently, these countries consider thorium fuel cycle (TFC) as an alternative option and show their interest in TFC only from position of its application in far future.

At the same time, a number of countries which recently jointed military treaties aim their scientific, research and design capabilities at development of independent national nuclear technologies with account that they have large stocks of thorium fuel.

The interest in study of thorium application is based on the following well-known reasons:

- decrease in nuclear power dependence on natural uranium;

- expected economic efficiency of the fuel cycle (supposed compatibility of majority technological processes with similar processes for uranium fuel in case of multi-component structure of the nuclear power);
- better neutronics and technological properties compared to uranium (in chemical compounds thorium is more stable and less chemical active; melting point of both metallic thorium and thorium dioxide is higher than that of uranium and uranium dioxide, respectively; higher thermal conductivity and lower temperature change for thorium dioxide compared to uranium dioxide; higher absorption cross section for thermal neutrons for thorium compared to uranium; lower radiation danger when daughter nuclides of thorium decay is releasing in the environment, mainly due to lower life-time of radon and radium compared to daughter nuclides of uranium);
- qualitative improvement of neutron balance in thermal reactor up to CBR=1 and breeding regimes;
- opportunity to eliminate enormous amounts of plutonium;
- opportunity of technical realization of these advantages of TFC in nuclear reactors.

Analysis of available references shows that there were practically no special studies of nuclear power facilities with thorium fuel. As a rule, nuclear reactor parameters related, first of all, to natural indices of fuel cycle were studied. Therefore, it is difficult now to definitely estimate from all sides safety level of nuclear plants when transferring from uranium to thorium fuel cycle.

From one hand, application of uranium-thorium fuel cycle in nuclear reactors can be characterized by the following safety-enhancement features of this fuel:

- higher melting point and thermal conductivity as well as good radiation stability contribute to workability and reliability of uranium-thorium fuel rods;
- use of uranium-thorium fuel in thermal reactors improves their breeding parameters and provides lower reactivity change with burnup for reactor fuel cycle;
- besides, fission products of ^{233}U have in thermal reactors lower neutron capture cross sections compared to ^{235}U and plutonium because of decrease (by ~10% - 20%) in yield of Xe and Sm which determine reactor poisoning. Thus, relative poisoning by such fission products with high neutron capture cross sections as Xe and Sm is lower and, hence, reactivity margin for compensation of fuel burnup in reactor fuel cycle is also lower [3];
- higher in absolute value Doppler reactivity coefficient;

- use of uranium-thorium fuel in fast reactor core provides negative void reactivity effect compared to uranium-plutonium fuel loading [3].

However, on the other hand, uranium-thorium fuel has a number of negative features:

- lower compared to $(U\text{-}Pu)O_2$ compatibility of metallic uranium-thorium alloys with structural materials from stainless steel [3];
- transmutation of ^{232}Th into ^{233}U is accompanied by production of intermediate nucleus ^{233}Pa with high neutron absorption cross section in thermal spectrum and with rather high half-decay period (~ 27 days). Protactinium parameters have negative impacts on reactivity change in time. When protactinium nuclei are decayed, rather high reactivity is released which by different estimates is 2%-6%. Such a reactivity release requires additional control system for compensation of this effect [3];
- delayed neutron fraction for ^{233}U ($\beta_{eff}\approx$ 0,0027) is lower than for ^{235}U ($\beta_{eff}\approx$ 0,0065) and slightly higher than for ^{239}Pu ($\beta_{eff}\approx$ 0,0021), while for ^{232}Th ($\beta_{eff}\approx$ 0,0203) beta is higher than for ^{238}U ($\beta_{eff}\approx$ 0,0148). However, as a consequence of low fission cross section for thorium its contribution from fission by fast neutrons is small, thus, average delayed neutron fraction is lower for thorium fuel than for uranium one [3].

^{233}U has lower radioactive toxicity compared to ^{239}Pu. However, there are technological problems connected with high radioactive danger provided by accumulation of ^{232}U (up to ~0.10% - 0.15%) in thorium cycle. One of the daughter products of ^{232}U is γ-active ^{208}Tl with $E\gamma\approx$ 2,62 MeV/decay. Therefore, fuel rod manufacturing from regenerated uranium-thorium fuel, containing in uranium fraction more than 0.02% of ^{232}U, requires application of enhanced protection and automatization of the technology process.

Radioactive dangers of β- γ- active wastes of thorium and uranium-plutonium fuel cycles are approximately compared. However, amount of α- emitting radioactive nuclides in thorium fuel cycle is approximately 100 times lower than in uranium cycle. At least for the first 10^3 years the radioactive danger, which is determined as ratio of nuclide activity to its allowable concentration in water, is approximately 10 times lower for nuclides of thorium fuel cycle compared to uranium cycle. Radioactive dangers are compared in approximately 10^6 years.

Experts from different countries direct their efforts to studies of possible solutions of the problem of long-lived high-active actinides of uranium-plutonium fuel cycle, for instance, by their final disposal or burning in nuclear facilities. The conducted quantitative estimates showed that amounts of long-lived actinides, when using the uranium-thorium fuel cycle, can be decreased by several orders. However, this cycle, in its turn, produces enough amounts of active isotopes as a result of transmutation of Th, Pa and U nuclides. Decrease in mass of secondary actinides is necessary, but not sufficient condition, because finally a determined role is played by total radiotoxicity of all produced isotopes (with account for transition to equilibrium fuel cycles).

From viewpoint of minimization of nuclear material nonproliferation risk the uranium-thorium fuel cycle has two positive features. First, a concept of "denaturated" fuel can be applied for ^{233}U, i.e. its dilution by non-fissile materials, for instance, by ^{238}U, while for fissile plutonium there are no natural denaturating isotopes. Second, a factor which makes difficult ^{233}U stealing and its use in military purposes is γ-activity typical for thorium cycle which also facilitates its detecting in case of nuclear material stealing.

5. Aspects of introduction of Th-U fuel cycle

To prepare U-Th fuel cycle corresponding technologies and their mathematical models should be developed with the use of which the following problems will be studied:

- accumulation and decay of ^{233}Pa (compared to ^{239}Np in uranium-plutonium fuel half-decay period and concentration of Pa in fuel is practically 10 times higher);
- reactivity monitoring and control especially in case of Th-Pu fuel (standard Ag-In-Cd control rod efficiency by ~70 %, while boron solution in coolant by ~30 % lower compared to UO_2 fuel) under conditions of low delayed neutron fraction;
- local positive reactivity effects in PWR and PHWR in case of their operation with Th-Pu fuel with high Pu content;
- increase (~1,25-1,5 times) of temperature reactivity coefficient for moderator in case of Th-Pu fuel (influence of this coefficient is positive in accidents with temperature rise and negative in accidents with overcooling).

Solution of problems related to reactivity effects requires their detailed analysis and, probably, development of new designs for control rods, new absorbing materials, including burnable absorbers.

Specific steps in realization of thorium introduction in the nuclear power can become:

- nearest 10 - 15 years - introduction of thorium in existing LWR and FBR for improvement of their operational and safety parameters practically without changes in their designs. Due to homogeneous introduction of thorium in fuel, heterogeneous disposition of thorium or thorium in combination with burnable absorber in separate fuel rods, use of thorium in movable reactivity compensators and creation of thorium blankets, the following problem can be solved:
    - à) optimization of reactivity effects;
    - á) improvement of physical and chemical properties of fuel;
    - â) increase of margins to ultimate parameters;
    - ã) decrease in stored energy and other inherent risks.
- nearest 10 - 20 years - optimization of design and operational conditions of fuel rods< fuel assemblies, core of existing reactors with account for possibility to use thorium and uranium-233 for safety and economic enhancement, decrease of generation rates for transuranic nuclides in the nuclear power system (all possible fuel cycles and nuclear power facilities should be analyzed in different combinations and assumptions);
- nearest 30 years - development and creation of demonstration thermal reactor with Th-U fuel with CBR=1;

- for 20 - 50 years - study and creation of methods for uranium-233 production both in critical and subcritical reactors with the use of electronuclear and thermonuclear neutron sources; search for optimal ways of conversion of transuranic nuclides into fissile nuclides as a limit - with transition of nuclear fuel cycle to regime of energy production without accompanying generation of transuranic nuclides.

Development of long-term concept and strategy of the nuclear power development supposes creation of mathematical models of the nuclear power structure with account for interrelations between different types of nuclear power facilities, nuclear fuel cycle enterprises (including fuel mining, different types of transformation, storage, disposal). Both concept and strategy of the nuclear power development should be based on :

- calculational estimates of long-term fuel balance in the system;
- material resources necessary for realization of the proposed strategy;
- calculational studies of nuclide and radioactivity balance not only in reactors, but also in the nuclear power system as a whole with account for long-term development perspectives;
- losses of both radionuclides and neutrons in different transformations and as a result of storage.

In RRC «Kurchatov Institute» such analysis is based on mathematical models in which the nuclear power structure and corresponding enterprises is described with various details.

Mathematical models provide calculations of main balance relations for amounts of nuclides and neutron balances both for uranium-plutonium and for uranium-thorium fuel cycles with account for fuel delays in external fuel cycle and losses of nuclides in reprocessing.

As input data dynamics of commissioning (decommissioning) of nuclear power plants of various types, times of fuel delays in external fuel cycle, parameters of initial and equilibrium fuel loadings in reactors, fuel stocks in nature and storages.

The fuel balance is calculated with account for :

- uranium mining;
- use of recycled uranium;
- use of high-enrichment weapons-grade uranium;
- use of high-weapons-grade plutonium;
- use of power plutonium from reactors of various types;
- use of thorium;
- use of accumulated U-233.

The power of the following accompanying enterprises can be specified in calculations:

- fuel mining and enrichment;
- reprocessing of irradiated fuel with account of time delays;
- waste disposal;
- other enterprises.

Amount of radionuclides in all objects of the nuclear power is calculated, if necessary, with estimate of potential ecological danger from different stages of the nuclear fuel cycle.

The calculations of balances then can be used for economic estimates and improvement of the nuclear power development strategy.

It is known that for effective sustaining of chain reaction in nuclear reactor the neutron balance in fuel cycle should be such that about 0.2-0.3 neutrons per fission is absorbed out of actinides. Neutron balances in different reactor fuel cycles when different nuclides are totally burned are shown in Table 1.

Table 1. Neutron excess when different nuclides are totally burned

	LWR		FR	
φ, n/cm^{2}s	10^{14}	10^{15}	10^{15}	10^{16}
^{235}U	0,62	0,65	0,88	0,90
^{238}U	-0,07	0,01	0,62	0,65
^{232}Th	0,24	0,24	0,39	0,39
^{239}Pu	0,72	0,83	1,46	1,51

We see from Table 1 that when considered family is totally transformed into fission products only fuel cycles based on ^{235}U, ^{232}Th and ^{239}Pu can be effective in thermal reactors without external neutron source. In fast reactors fuel cycle based on ^{238}U also become effective. Note, plutonium is produced in fuel cycles based on ^{238}U and ^{232}Th, when they are totally transformed into fission products. If we extract it in the process of nuclear reactor operation, then we decrease positive neutron balance of these fuel cycles and they become not effective.

In the process of this consideration we selected three nuclides which are expedient to use in further development of the nuclear power. These are ^{235}U, ^{239}Pu and ^{232}Th. As noted above, stocks of ^{235}U in Earth are limited. Therefore, the future nuclear power will evidently develop mainly due to ^{238}U and ^{232}Th.

To realize the large-scale nuclear power for long time it should meet the following requirements: economic efficiency, resources, safety, acceptability of environmental impact.

The economic efficiency and provision by resources can be reached with the use of the two-component nuclear power consisting of solid-fuel thermal and fast reactors. In such a structure efficiency of utilization of natural resources (uranium and/or thorium) can be significantly increased, uranium mining and, hence, radon release in biosphere can be decreased.

The ways of reaching necessary breeding level, safety enhancement of nuclear power facilities and decrease in capital costs for both types of the reactors are known now and time as well as financing are necessary for their realization. By the moment when the society understands need of the nuclear power development the two-component nuclear power technology will be practically prepared, although a lot should be made in the area of optimization of both nuclear power facilities and the nuclear power structure, including fuel cycle enterprises.

The search for ways of reliable radwastes disposition without doubt cannot be rejected, however, on the other hand, the possibility should also be considered not to dispose actinides, but to use them for energy production in the third component of the nuclear power, i.e. the possibility of fuel cycle closure not only on uranium and plutonium, but also on minor actinides. Fuel cycle on minor actinides can in a best way be closed in molten-salt reactors - burners which can be used in future also in thorium-uranium fuel cycle.

To estimate required fraction of burners in the nuclear power structure and their parameters, amounts of minor actinides and long-lived fission products to deal with in the nuclear power structure should be assessed. Each radionuclide sooner or later will reach its maximum amount which can be called equilibrium for constant total power of the nuclear power system. Equilibrium rate of radionuclide generation equals the rate of its decay.

The nuclear power based on thermal, fast and molten-salt reactors can for a long time operates without generation of large amounts of minor actinides. This will make the nuclear power more acceptable ecologically especially for next generations. If otherwise we additionally introduce ^{232}Th in fuel cycle of such a structure, then due to lower generation of transuranic radionuclides, we will be able to make the nuclear power even more ecologically safe and acceptable for the society. The use of ^{232}Th will increase the time of the nuclear power effective operation due to very large resources of thorium.

To clarify the problem of possibility of ^{232}Th introduction in multi-component structure of the large-scale nuclear power, problem of joint use of ^{238}U and ^{232}Th is considered in this paper.

In proposed interpretation of the development strategy the nuclear power is not an alternative to the power based on organic fuel, but is its necessary addition. Different nuclear reactors do not compete each other, but supplement each other, allowing by the optimal way to show advantages of each type of nuclear power facilities.

Nowadays Th-U fuel cycle is still not practically used in the nuclear power. However, as seen from Table 1, ^{232}Th is more effective compared to ^{238}U as fuel in thermal neutron spectrum and less effective in fast reactor spectrum. Therefore, if disposing it in blankets of fast reactor then ^{233}U will be generated which then can be used as fuel in considered three-component structure of the nuclear power - in thermal and molten-salt reactors.

Annular world production of thorium concentrate is 31 000 t, while stocks of relatively cheap thorium is $3{,}3 \cdot 10^6$ t. As well known, practically all natural thorium consists of isotope ^{232}Th. Therefore, thorium can be used as effective in the nuclear power as ^{238}U.

While disposing thorium in fast reactor blankets and using ^{238}U as a fuel, we will also generated plutonium in the core. Therefore, in fact we will have Th-U-Pu fuel cycle. It goes without saying that besides ^{238}U plutonium already generated early can be also used in fast reactor.

Preliminary calculations of equilibrium amounts and activity of heavy radionuclides for U-Pu fuel cycle in the three-component nuclear power reduced to 1 GWe were performed. Fraction of fast reactors in this structure was supposed 38%, fuel cycle length is 3 years, annular reactor loading is 570 kg ^{238}U. Heavy nuclides, except U and Pu, are loaded into MSR, while U and Pu returns in the fuel cycle. In this scheme 2.2% of equilibrium amounts of Pu returns into thermal reactor and 0.6% goes to MSR. Fraction of thermal reactors in this structure is 51%, fuel cycle length is 3 year, annular reactor loading is 430 kg ^{238}U. Heavy nuclides, except U and Pu, are loaded into MSR, while U and Pu returns in the fuel cycle. Fraction of molten-salt reactors in this structure is 11%.

Calculations were also made for Th-U-Pu fuel cycle of the three-component structure of the nuclear power reduced to 1 GWe. Fraction of fast reactors in this structure was supposed 17%, fuel cycle length is 3 years, annular reactor loading is 130 kg ^{238}U and 90 kg ^{232}Th. Heavy nuclides, except Th, U and Pu, are loaded into MSR, while Th, U and Pu returns in the fuel cycle. In this scheme 3.2% of equilibrium amounts of ^{233}U returns into thermal reactor and 0.8% goes to MSR, 1% of equilibrium amounts of Pu goes to MSR. Fraction of thermal reactors in this structure is 76%, fuel cycle length is 3 year, annular reactor loading is 780 kg ^{232}Th. Heavy nuclides, except Th, U and Pu, are loaded into MSR, while Th, U and Pu returns in the fuel cycle. Fraction of molten-salt reactors in this structure is 7%.

The results obtained showed that activity of heavy radionuclides with average and long-term life period (half-decay period of 10 years and higher) by an order of magnitude higher in the three-component nuclear power based on U-Pu fuel. At the same time, activity of heavy radionuclides in fast reactor with U-Pu fuel cycle is approximately 2 times as much as for similar reactor with U-Th fuel cycle. Activity of heavy nuclides in MSR with U-Pu fuel cycle is by an order of magnitude higher than activity in MSR with U-Th fuel cycle.

When the nuclear power system is fuelled by ^{238}U, activity of equilibrium amounts of radionuclides ^{240}Pu, ^{239}Pu, ^{241}Am, ^{243}Cm, ^{237}Np in fast reactor is by an order of magnitude higher than in fast reactor when the nuclear power system is fuelled by ^{238}U and ^{232}Th. When the nuclear power system is fuelled by ^{238}U and ^{232}Th, in fast reactor activity of equilibrium amounts of radionuclides ^{232}U - by 5 orders, ^{233}U – by 7 orders, ^{234}U – by 2 orders, ^{231}Pa – by 7 orders, ^{227}Ac – by 7 orders, ^{236}U – by an order, ^{229}Th - by 6 orders, ^{232}Th - by 10 orders, ^{230}Th - by 2 orders, ^{235}U – by an order, ^{226}Ra - by 2 orders and ^{244}Pu – an order of magnitude higher than in fast reactor when the nuclear power system is fuelled by ^{238}U. As noted above, total activity of radionuclides in fast reactor with U-Pu fuel cycle is about 2 times higher than for similar reactor with U-Th fuel cycle.

When the nuclear power system is fuelled by ^{238}U, in thermal reactor activity of equilibrium amounts of radionuclides ^{241}Pu, ^{242}Pu, ^{243}Cm, ^{242m}Am, ^{246}Cm, ^{247}Cm, ^{247}Bk is by 3 orders of magnitude, ^{244}Cm, ^{240}Pu, ^{241}Am, ^{239}Pu, ^{245}Cm, ^{250}Cf, ^{249}Cf, ^{244}Pu, ^{251}Cf, ^{248}Cm, ^{250}Cm – by 3 orders of magnitude higher than in thermal reactor when the nuclear power system is fuelled by ^{238}U and ^{232}Th. When the nuclear power system is fuelled by ^{238}U and ^{232}Th, in thermal reactor activity of equilibrium amounts of radionuclides ^{232}Th - by 10 orders, ^{233}U – by 8 orders, ^{227}Ac – by 6 orders, ^{232}U, ^{231}Pa, ^{229}Th – by 5 orders, ^{238}U – by 4 orders, ^{230}Th, ^{226}Ra - by 3 orders, ^{234}U, ^{236}U, ^{243}Am, ^{235}U – by 2 orders higher than in thermal reactor when the nuclear power system is fuelled by ^{238}U. Total activity of equilibrium amounts of heavy radionuclides with half-decay period of 10 years and higher in thermal reactor is higher when the nuclear power system is fuelled by ^{238}U due to higher activity of ^{241}Pu. Activity of equilibrium amounts of ^{241}Pu in U-Pu fuel cycle is $1{,}805 \cdot 10^{18}$ Bk. The highest activity of equilibrium amount in thermal reactor with U-Th fuel cycle has ^{238}Pu, its activity is $1.63 \cdot 10^{16}$ Bk.

When the nuclear power system is fuelled by ^{238}U, in MSR activity of equilibrium amounts of radionuclides ^{244}Cm – by 2 orders, ^{250}Cf, ^{246}Cm, ^{240}Pu, ^{243}Am, ^{245}Cm, ^{251}Cf, ^{249}Cf, ^{242}Pu, ^{248}Cm, ^{247}Bk, ^{250}Cm, ^{247}Cm, ^{230}Th – by an order of magnitude higher than in MSR when the nuclear power system is fuelled by ^{238}U and ^{232}Th. When the nuclear power system is fuelled by ^{238}U and ^{232}Th, in MSR activity of equilibrium amounts of radionuclides ^{233}U, ^{229}Th – by 6 orders, ^{232}U, ^{227}Añ - by 5 orders, ^{231}Pa, ^{230}Th, ^{226}Ra - by 4 orders, ^{234}U - by 3 orders, ^{236}U, ^{235}U, ^{238}U - by 2 orders, ^{243}Cm and ^{237}Np – by an order of magnitude higher than in MSR when the nuclear power system is fuelled by ^{238}U. Total activity of equilibrium amounts of heavy radionuclides with half-decay period of 10 years and higher in MSR is higher when the nuclear power system is fuelled by ^{238}U due to higher activity of ^{244}Cm. Activity of equilibrium amounts of ^{244}Cm in U-Pu fuel cycle is $1{,}049 \cdot 10^{17}$ Bk. The highest activity of equilibrium amount in MSR with U-Th fuel cycle has ^{241}Pu, its activity is $1.763 \cdot 10^{16}$ Bk.

One of the directions under development last years in RRC KI is development of thorium reactor-nonproliferator VVER-T [4,5]. This development is performed related to operating reactor VVER-1000.

Conclusions

Mathematical model was developed for calculation of equilibrium amounts and activities of heavy radionuclides of three-component structure of the nuclear power, operating with U-Th fuel and reduced to 1 GWe.

Fraction of fast reactors in this structure was supposed 17%, fuel cycle length is 3 years, annular reactor loading is 130 kg ^{238}U and 90 kg ^{232}Th. Heavy nuclides, except Th, U and Pu, are loaded into MSR, while Th, U and Pu returns in the fuel cycle. In this scheme 3.2% of equilibrium amounts of ^{233}U returns into thermal reactor and 0.8% goes to MSR, 1% of equilibrium amounts of Pu goes to MSR. Fraction of thermal reactors in this structure is 76%, fuel cycle length is 3 year, annular reactor loading is 780 kg ^{232}Th. Heavy nuclides, except Th, U and Pu, are loaded into MSR, while Th, U and Pu returns in the fuel cycle. Fraction of molten-salt reactors in this structure is 7%.

Calculations were also made for U-Pu fuel cycle of the three-component structure of the nuclear power reduced to 1 GWe. Fraction of fast reactors in this structure was obtained in calculations as 38%, fuel cycle length is 3 years, annular reactor loading is 570 kg ^{238}U. Heavy nuclides, except U and Pu, are loaded into MSR, while U and Pu returns in the fuel cycle. In this scheme 2.2% of equilibrium amounts of Pu returns into thermal reactor and 0.6% goes to MSR. Fraction of thermal reactors in this structure is 51%, fuel cycle length is 3 year, annular reactor loading is 430 kg ^{238}U. Heavy nuclides, except U and Pu, are loaded into MSR, while U and Pu returns in the fuel cycle. Fraction of molten-salt reactors in this structure is 11%.

The results obtained showed that activity of heavy radionuclides with average and long-term life period (half-decay period of 10 years and higher) by an order of magnitude higher in the three-component nuclear power based on U-Pu fuel. At the same time, activity of heavy radionuclides in fast reactor with U-Pu fuel cycle is approximately 2 times as much as for similar reactor with U-Th fuel cycle. Activity of heavy nuclides in thermal reactor with U-Pu fuel cycle is by two orders of magnitude higher than similar activity in thermal reactor with U-Th fuel cycle. Activity of heavy nuclides in MSR with U-Pu fuel cycle is by an order of magnitude higher than activity in MSR with U-Th fuel cycle.

The results obtained showed that uranium-plutonium and uranium-thorium fuel cycles in the three-component structure of the nuclear power has approximately the same radiotoxicities of average and long-lived radionuclides. Slightly higher radiotoxicity has uranium-plutonium fuel cycle.

Additional studies are required to clarify radiotoxicity of uranium-plutonium and uranium-thorium fuel cycles in the three-component structure of the nuclear power for short-lived radionuclides.

Neither uranium-plutonium nor uranium-thorium fuel cycles has significant advantages in radiotoxicity over each other. Therefore, based on the results of this work we can recommend the most profitable fuel cycle for the three-component structure of the nuclear power. Solution of the problem which of the considered fuel cycles is the most economically profitable requires additional studies on developed mathematical model with the use of economic data base for closed fuel cycle enterprises.

In frames of international project on innovative reactors and fuel cycle it would be expedient as a preparation to the large-scale nuclear power to consider the following demonstration projects:

1. Reactor of small power≤50 MW, transportable with fuel cycle of 10-15 years, without refueling on site, with corresponding infrastructure;
2. Closure of U-Pu and Th-U fuel cycles by non aqueous methods including radwaste treatment;
3. Thermal reactor of large or average power with Th-U fuel and CBR=1;
4. Fast reactor of large or average power with U-Pu fuel and CBR=1; with uranium or thorium blankets;
5. Molten-salt reactor - burner of transuranic nuclides and long-lived fission products;
6. Technologies of expansion of the nuclear power utilization sphere (high-potential heat, desalination, coal gasification, etc.).

Some of these six projects can appear preferable for different countries.

The international project should be based on a set of views on all nuclear power system with account for regional features of demands and economic systems.

The degree of danger in view of time for manufacturing of a nuclear explosive is reduced from the higher for plutonium and highly enriched uranium up to the lowest for natural uranium and thorium

The (Th-U) closed fuel cycle is more proliferation resistance of nuclear materials than (U-Pu) fuel cycle

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