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NEW STAGE IN RUSSIA'S NUCLEAR ENERGY STRATEGY

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This article discusses a technological platform of nuclear energy for implementing the proposed Atomic Project 2.0 which is focused on the country's objectives in sustainable development, including the development of advanced innovative technologies and materials, and producing examples of new equipment. The basis of modern nuclear power in Russia and the world is water-cooled pressurized reactors with capacity 1000 MW or more, and there are no objective prerequisites for changing this paradigm in the foreseeable future. In this connection, VVER technology remains the most important tool for achieving the strategic goals of our country in the field of nuclear energy. The existing strategic plans relegate extensive adoption of fast reactors and NFC closure based on them to the 2030s, which can be viewed as the customary maximalism in the face of the current moderate notions concerning growing demand for nuclear generation. The prospects for the introduction of small and medium-sized nuclear power plants, taking into account the forecasted demand for electricity and the territorial distribution of generation in Russia, as well as the opportunities for foreign business, promise a new quality of nuclear energy production and a fundamentally different niche in the energy basket. Perhaps the strongest indication of the current stage of progress in nuclear energy is a resurgence of expansion into new areas of energy consumption. It must be assumed that a version of the nuclear energy strategy worthy of presentation in Atomic Project 2.0 will incorporate development of directions of heat supply, hydrogen production, and seawater desalination by means of nuclear technologies for the home and international markets, as well as promising areas such as molten-salt nuclear technologies or hybrid systems.

At present, when the idea of organizing Atomic Project 2.0 is promoted in the country as being oriented towards the goals of sustainable development and including the development of advanced innovative technologies, materials, and examples of new technology in the field of the use of atomic energy, there is every reason to recall the strategy of the Atomic Project USSR – a wide front of work 'on the uranium problem' with mandatory reservation of technical directions in order to secure solutions of the problems posed.

Nuclear Energy Strategy-2018. In the last ten years the strategic view of the nuclear energy industry in Russia was largely formed on the basis of the conceptual work of two large groups of researchers [1, 2]. Their main result was a practical consensus both in the scientific community and in the industry leadership regarding the basic provisions of the country's nuclear energy development strategy up to the middle of the 21st century:

– the technological basis of a two-component nuclear energy system is the existing and developed VVER reactors and commercially developed fast reactors;

– the key direction is a transition to a two-component structure based on thermal and fast reactors with fuel cycle closure.

These provisions were formalized by the approval of Strategy-2018 by the State Corporation Rosatom in 2018 [3].

It should be noted that in Strategy-2018 the problem of long-term fuel supply for the developing nuclear energy industry is considered as a key problem, although the objective trend is a constant reduction in the estimated demand for electricity

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and, accordingly, the predicted capacities of nuclear energy. Since the electric power estimates equal to 150–200 GW by the end of the 21st century were made, a more than two-fold reduction occurred [1, 2]. We point out that difficulties with fuel supply for the growing nuclear energy industry were already predicted by the end of the 20th century, but they were constantly postponed for many decades, and this process continues.

Along with the basic directions – significant savings in natural uranium during the development of VVER and the introduction of improved sodium fast reactors, Strategy-2018 provided for safety solutions, primarily the development of a fast reactor with a lead-coolant BREST reactor, as well as the possibility of increasing the uranium resource base, the introduction of thorium into the nuclear fuel cycle, and the fundamental feasibility of a thermonuclear source of neutrons for the production of nuclear fuel.

A waiting list of promising reactor technologies was formulated in the experts' community has developed a common vision of the "waiting list" for promising reactor technologies [4]. At the same time, the characteristics of the development of nuclear energy other than the fuel supply, such as expanding the power range to diversify customers, non-electric use of nuclear energy, and others, are considered in a fragmented manner in Strategy-2018.

The works performed in 2018 once again confirmed that attempts to present in detail the structure of the nuclear energy system in the second half of the 21st century do not lead to unequivocal results that give good reasons for strategic decisions at the present time. In connection with this, in a long-term strategy, innovative ideas for which there is still not enough objective data to determine the time horizons of development should not be excluded from consideration.

Strategy for the development of nuclear energy at the present time. Over the past period, in addition to the systematic construction of nuclear power plants with modern VVER projects and the development of a program for the construction of a new generation of nuclear icebreakers based on the serial reactor installation RITM-200, there have been noticeable changes and refinements in providing the raw material base of nuclear energy, including through internal technological development – the development of the VVER-S project with electric power ~600 MW for the Kola region has begun, and the projects for the fast reactor BN-1200 and the thermal VVER-1300 (VVER-TOI) are being finalized.

Two problems currently stand in the way of the large-scale use of fast reactors:

– technical and economic indicators of electricity production, which do not yet allow competition with other energy sources, including thermal reactors such as VVER;

– insufficient development of closed NFC technologies as a systemic problem of nuclear energy.

Fast reactors are considered as a system-forming factor in a closed NF of nuclear energy, whose practical development of technologies begins with the use of the BN-800 Beloyarsk NPP as the base reactor. On this basis, it is planned to develop multiple recycling technology that minimizes the accumulation of spent nuclear fuel, reliable controlled storage of short-lived radwaste followed by final isolation in geological formations and transmutation (destruction) of long-lived radwaste. In the future, it is planned to create an industrial infrastructure for a closed nuclear fuel cycle using fast reactors.

The most significant event along this path was the start of construction of the innovative lead-cooled experimental demonstration power unit BREST-OD-300, which turned the process of selecting the type of fast reactor for the sustainable development of nuclear energy from unproductive and dependent mainly on the enthusiasm of the developers of economic comparisons of projects of fundamentally different levels elaboration into an objective comparison of the achieved practical results. The implementation of the BREST project with a large number of new and radical technical solutions will create an objective basis for the declared, exceptionally high technical and economic indicators.

The existing strategic plans relegate extensive adoption of fast reactors and NFC closure on their basis to the 2030s, which can be assessed as traditional maximalism in the face of current moderate notions on growth in nuclear energy demand, but timely in the event of a significant change in the rate of nuclear energy development. Nevertheless, the fundamental trend at the current stage in the development of nuclear energy has become not even progress towards solving its internal technological and resource problems, but a frontal expansion of the use of this method of energy production for sustainable economic and environmental progress.

The coronavirus pandemic, which has had a significant impact on the global economy and its energy sector, has demonstrated the critical importance of the sustainability of energy supplies in times of crisis, which nuclear energy has proven [5]. Pandemic-intensified predictions of the imminence of a low-carbon energy transition have sparked an explosion in the discussion of 'green investment' not only in renewable energy sources, but also in innovations such as the use of nuclear energy beyond electricity generation. The rate of predicted growth in the use of renewable energy sources will depend on the development of efficient technologies for long-term energy storage and, as a result, stimulate a tandem of nuclear energy and renewable sources in energy systems.

The home-grown energy sector has not remained aloof from this global trend. At a UN climate change conference in Glasgow (COP26), the Russian side stated that without nuclear energy it would not be possible to achieve the declared climate goals. The four low-carbon energy sources are a green square with nuclear and hydro at the bottom providing base load and wind and solar at the top providing peak load. The fundamental expansion of the scope of the nuclear energy use is the objective basis for Atomic Project 2.0.

Advancement along the entire front. The basis of modern nuclear energy in our country, as well as in the world, is water-cooled reactors with an electric power 1000 MW or more, and there are no objective prerequisites for changing this paradigm in the foreseeable future. At the same time, VVER remains the most important tool for achieving the strategic goals of our country in the field of nuclear energy. There is a continuous evolution of high-power reactors: from the No. 5 unit of the Novovoronezh NPP in 1980 to NPP-2006 with the currently most powerful power unit VVER-1200 and VVER-TOI with a VVER-1300 reactor. Pressurized water-cooled reactors are not only the practical basis of nuclear energy for the coming decades, but also, as expected, its significant component until the end of the century for our country and the world, as well as for home-grown reactor technology on the world market. At the same time, a fundamental expansion of the power range in the direction of small installations is a long-foreseen development.

The prospects for the introduction of small and medium-sized nuclear power plants, taking into account the demand for electricity and territorial distribution in Russia, as well as the opportunities for foreign business, offer a new quality of nuclear energy production and a fundamentally different niche in the energy basket. But, small nuclear power plants (SNPPs), with their obvious advantages over the customary energy sources in hard-to-reach areas, despite the desire and reasonable hopes of the developers, have not yet become a significant direction in the energy sector. The history of the intensive development of small nuclear power plants in the 1960s and 1970s both in the USA and the USSR showed that interest in them was associated not so much with the desire to provide hard-to-reach territories with nuclear energy, but with the needs of defense departments. This activity decreased markedly in the 1980s. A new surge of interest in SNPP has been observed in the world community over the past few years. The review of the technological development of small reactors, regularly published by the IAEA, lists several dozen projects from different countries. However, only a few of them can claim to be implemented before 2030, and most of them relate to pressurized water reactors in the electric power range 50–200 MW.

Our country's leadership views the development of small nuclear power plants objectively. A large maritime boundary with dispersed consumers is particularly suitable for this type of energy supply. Russia has a unique reserve for its further development. Since 1954, the country has developed four generations of reactor plants for civilian nuclear ships. A unique nuclear power plant for coastal power supply, located on a non-self-propelled barge (FNPP Akademik Lomonosov), has been developed and put into operation; it has become the northernmost nuclear power plant in the world. There is already a project designed to generate electricity at sites with a wide range of natural and climatic conditions and the possibility of equipping with cogeneration and desalination plants [6]. A site in Yakutiya has been selected for this installation; the expected commissioning date is 2028.

The program for the introduction of small nuclear power plants has the required depth of deployment. Several projects, starting with electric power 6 MW, including the Shelf-M installation, are offered by the Dollezhal Research and Development Institute of Power Engineering (NIKIET). The experience of the National Research Center Kurchatov Institute in the development of power plants based on the direct thermoelectric conversion of thermal energy into electrical energy (in 1964 – the world's first such installation Romashka, and since 1982 – ATES Gamma, which has operated for 15 years) made it possible to propose an independent class, including unattended self-regulating small nuclear power plants with direct energy conversion, electric power from 1 to 500 kW, and service life 10 or more years. In recent years, these works have been given a powerful impetus [7]. China has begun construction of a 100 MW nuclear unit.

The need to solve regional economic problems, as well as the objective needs of the external market, brought back to life the development of reactors with an average electric power of 300–700 MW, which were intensively developed at the first stage of the introduction of peaceful atom into the energy sector, and are currently prevailing for non-nuclear power plants worldwide. A fundamental practical step in this direction is the decision to build replacement capacities at the Kola NPP based on new 600–700 MW VVER reactors. The construction of such units will become the basis for proposals on the foreign market.

The proposals of the Kurchatov Institute for the development of the same type of nuclear power plants of different capacities on the basis of the basic design coud be promising. Such projects can be nuclear power plants:

– on the basis of a four-loop reactor plant of the AES-2006 project (1200 MW) or VVER-TOI (1300 MW) – a three- and two-loop plant with electric power 900–1000 and 600–700 MW, respectively;

– on the basis of the four-loop reactor plant VBER-600 – two-, three-, and six-loop plant with electric power 300, 450, and 900 MW, respectively.

Installations with such capacities can meet the demands of the world's customers.

In this capacity range, the joint proposal of the Kurchatov Institute and Gidropress OKB for the development of 100–200 MW VVER-I, operating on natural circulation with the steam generators placed inside the reactor vessel, is interesting.

The most significant sign of the current stage of progress in nuclear energy is the revival of a trend weakened by severe accidents but never disappeared – the desire to spread into new areas of energy consumption. This desire was born simultaneously with the beginning of the practical use of nuclear energy – success in the nuclear submarine fleet, a failed attempt to create nuclear aviation, a little later – introduction into energy supply, including radioisotope energy for the exploration of near, then deep space.

Ground-based nuclear power has also shown a constant desire to go beyond power generation. The history of the home-grown energy industry includes the almost completed large-scale nuclear heat supply (ACT), nuclear desalination (BN-350), brought up to ready-to-implement technical designs of high-temperature reactors for various technological processes in a wide range of capacities.

It should be noted that the use of high-temperature reactors to give a new quality to nuclear technology – their introduction into the energy industries, including nuclear-hydrogen energy and the implementation of highly efficient heat and electricity cogeneration cycles, was one of the areas actively developed at the Kurchatov Institute in the 1970–1980s. In 1995–2015, HTGR projects were again returned (MGR-100, GT-MGR – a joint Russian-American project, etc.). At present, this is the basis for the development of high-temperature gas-cooled reactors of a new generation. All this is still "on the waiting list," but today it is already being discussed as real prospects.

It must be assumed that the nuclear energy strategy presented in Atomic Project 2.0 will include the development of hydrogen production, seawater desalination, and heat supply using nuclear technologies for the home-grown and international markets, as well as promising areas of development, such as molten-salt nuclear technologies or hybrid systems.

Molten-salt circulating-fuel reactors (MSRs) are, in principle, more flexible than solid-fuel reactors. The possibility of continuous correction of the composition in the liquid phase almost removes the restrictions on fuel burnup. Liquid fuel composition based on fluoride melt has high radiation and thermal resistance as well as chemical inertness and can circulate in the absence of pressure in the primary reactor circuit at high temperature. Successful confirmation of the basic principles of the work of the MSR was obtained in the 1970s on an experimental reactor in the United States, and at the same time research began at the Kurchatov IAE (now NRC Kurchatov Institute). In the 2000s, the concept of MSR again attracted the world's attention with the possibility of transmutation of long-lived actinides. Since then, the MSR, as promising reactor technologies, has not left the waiting list. The timing of their implementation depends on the practical demonstration of stable structural materials of the primary loop [3].

Without going into the advantages and disadvantages of the thorium fuel cycle, it should be recognized that the transition to thorium requires exceptionally good reasons. The strategy adopted in 2018 [3] for the development of nuclear energy notes that the involvement of thorium in nuclear energy when uranium reserves are depleted will require the development of new technologies and the creation of an expensive industrial fuel cycle infrastructure. So, thorium must not be expected to enter practical power engineering soon, at least as long as it works in an open fuel cycle.

The use of thorium as well as molten-salt technologies in nuclear production is currently associated with an idea that remained unknown for many years. It was expressed by I. V. Kurchatov and received new life at the initiative of the

Kurchatov Institute [8]. A thermonuclear source of high-energy neutrons for the efficient production of nuclear fuel, i.e., a hybrid fusion-fission reactor, can be built much sooner than the problems standing in the way of thermonuclear energy, primarily plasma loads on the first wall, are solved.

The potential for fuel production in thermonuclear reactors is significantly higher than in any others, since at the same power it produces about an order of magnitude more neutrons that can be used to convert raw into fissile isotopes than in fission reactors. For a thermonuclear reactor producing fuel for fission reactors, there is no need for a high energy multiplier due to a thermonuclear reaction. Finally, the operation of a hybrid thermonuclear reactor is assumed to be in the regime of continuous purification of the fuel composition, in which a new fissile isotope is produced under conditions of maximum suppression of nuclear fission. This guarantees an almost complete absence of residual energy release in the blanket of the hybrid reactor, and hence fission products. All this makes the idea of a symbiosis of nuclear energy fission and fusion promising.

In summary, one should not forget the conviction of veterans of the nuclear industry that for nuclear energy, which can rightfully be called multicomponent, nothing is impossible in principle and I. V. Kurchatov's position on an "offensive along the entire front" is correct.

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