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Scientific Session of the General Meeting of RAS Members "75 Years of the Nuclear Industry: the Contribution of the Academy of Sciences"

Bicomponent Nuclear Power

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Abstract—Prospects and problems of the development of modern nuclear power, as well as ways to solve them are analyzed in this article, which was prepared on the basis of a report at the General Meeting of RAS members on December 8, 2020. In late 2018, the Presidium of Rosatom's Scientific and Technical Council approved the Strategy for the Development of Nuclear Power, which envisages reaching an NPP capacity in the range of 70–90 GW by the end of the century. The strategy assumes that by the middle of the century, nuclear power will become bicomponent: along with the technologies of the existing nuclear power, which currently uses an open nuclear fuel cycle and thermal neutron reactors, a new branch of nuclear power will be created on the basis of fast reactors with a closed nuclear fuel cycle. Its development will make it possible to reduce the accumulation of spent nuclear fuel, reduce the volume of radioactive waste, increase the efficiency of the use of uranium raw materials and environmental indicators, and maintain the competitiveness of nuclear energy in comparison with other generations.

Keywords*:* nuclear power, Strategy for the Development of Nuclear Energy, fast reactors, bicomponent nuclear power, competitiveness, safety, radiation equivalence.

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The possibility of creating nuclear power was prepared by the academic work of the late 19th and first half of the 20th century, including by Russian scientists G.A. Gamov, Ya.B. Zel'dovich, D.D. Ivanenko, I.V. Kurchatov, K.A. Petrzhak, G.N. Flerov, Ya.I. Frenkel', and Yu.B. Khariton. However, it was the prospect to create nuclear weapons that accelerated the development of nuclear reactors. The first reactors in the United States (Chicago Pile-1, CP-1), where a controlled chain reaction was first obtained in 1942, and its analogue F-1 (1946) at the site of Laboratory No. 2 of the USSR Academy of Sciences (now NRC Kurchatov Institute) were hastily built to test the feasibility of nuclear reactors and to obtain laboratory quantities of plutonium, which does not exist in natural conditions. Their experience was used to create the industrial reactors B in Hanford (US) and A at the Mayak plant in the city of Ozersk, Chelyabinsk oblast, which solved the problem of producing weapons-grade isotopes (Pu). The work developed within the USSR Academy of Sciences in the 1930s–1940s to study the atomic nucleus and in 1942 to study the possibility of creating a uranium bomb or uranium fuel (State Defense Committee (*GKO*) Resolution no. 2352ss) was boosted in August 1945, after the explosion of the first American bombs in Hiroshima and Nagasaki, by the creation of a Special Committee under the USSR State Defense Committee. However, as soon as October 1945, P.L. Kapitsa sent to the First Main Directorate under the USSR Council of People's Commissars (the predecessor of the Ministry of Medium Machine Building and the current Rosatom) a memorandum "On the Use of Intranuclear Energy

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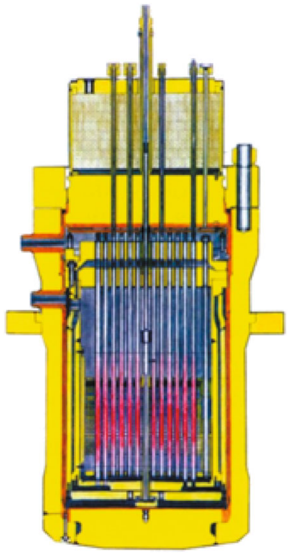

Fig. 1. First pressurized reactor VM-A.

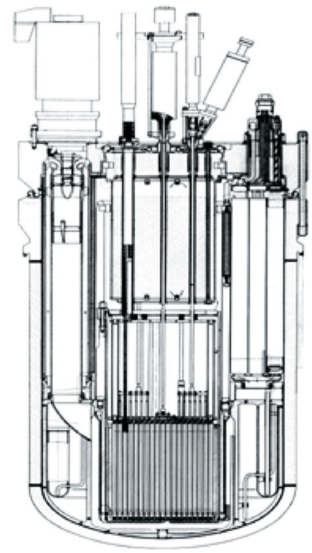

Fig. 2. Monoblock installation MBU-40.

for Peaceful Purposes." Kurchatov confirmed the possibility to use the design of the A reactor, created to breed plutonium for the production of heat and electricity. The resolution of the country's government on the construction of the first Soviet nuclear power plant was adopted in May 1949, i.e., several months before the successful test of the first Soviet nuclear charge.

The design by N.A. Dollezhal' of a uranium–graphite water-cooled reactor, based on data from Soviet intelligence, the concept of which differed from the American one, formed the basis of one of the two branches of the development of nuclear power in the Soviet Union. The first nuclear power plant in Obninsk (1954) and the Siberian nuclear power plant (1958) at the Siberian Chemical Combine near Tomsk laid the foundation for the channel trend in reactor building in our country, which was later continued by a series of nuclear power plants with a high-power channel-type reactor (RBMK).

The appearance of the second branch of nuclear power—pressurized water-cooled water-moderated reactors—was also associated with problems of defense. The first pressurized reactor VM-A (Fig. 1) was designed by Dollezhal' for a nuclear submarine that entered service in 1958. The development of this trend within the Navy was accompanied by the transition from loop designs of reactor facilities to block designs with a decrease in their weight, size, and cost. However, a real breakthrough was the proposal of Dollezhal' on the design of the MBU-40 monoblock installation (Fig. 2), which farsightedly anticipated promising solutions in nuclear power. Integral-type reactor installations, implemented for defense tasks, became the prototype of many reactors that are being developed in the world today, for example, BN-1200 (Fig. 3).

Power units operating and under construction in Russia are shown in Fig. 4. Modern nuclear power in Russia accounts for 12.0% of the installed capacity of power generating stations and more than 20% of the generated (in 2020) electricity. Noteworthy is also the dynamics of the development of nuclear power in our country (Fig. 5), where the total electricity production has remained at the level of 1000–1100 bln kWh over the past 30 years. In 2000, when this level was below 900 bln kWh, Russia's nuclear power reached an indi-

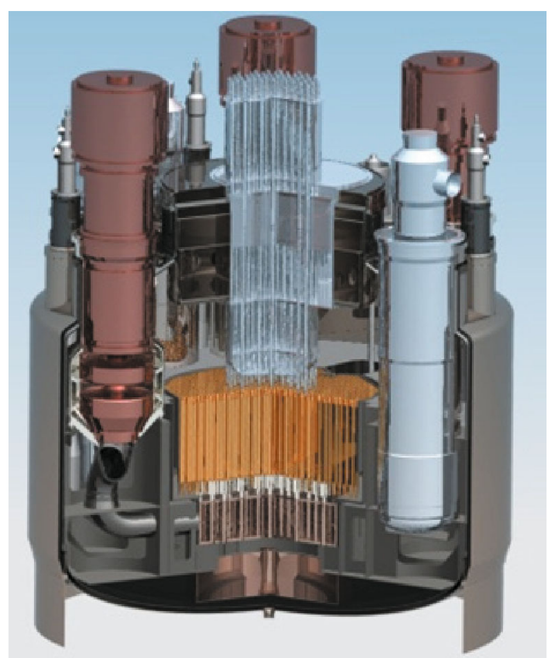

Fig. 3. Reactor installation BN-1200.

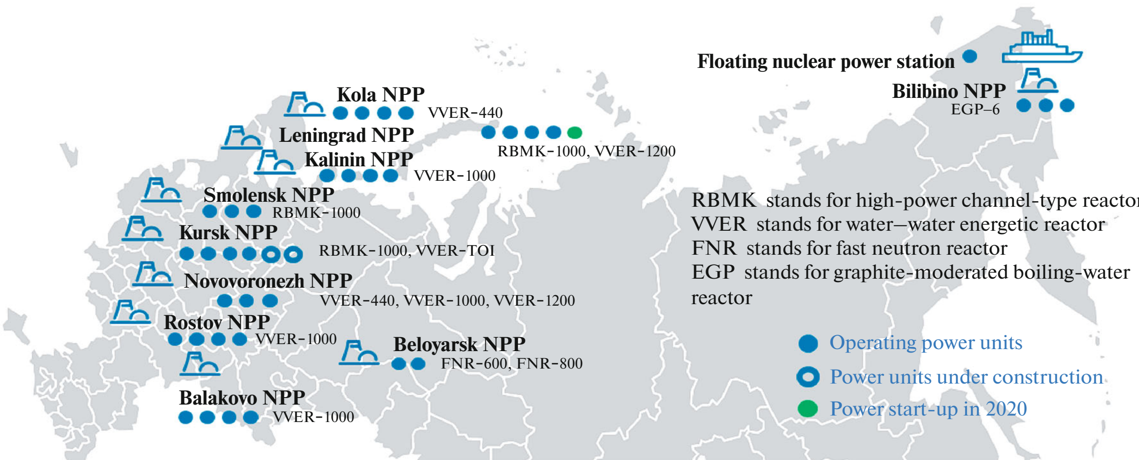

Fig. 4. Location map of power units of Russian NPPs operating and under construction.

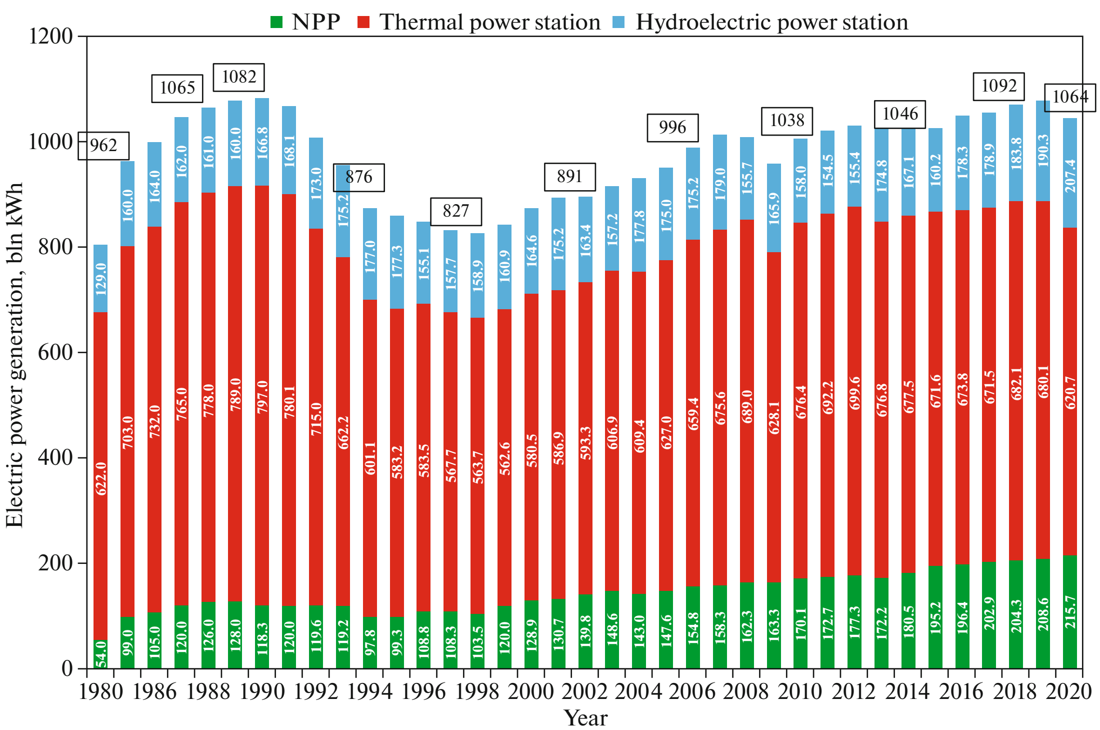

Fig. 5. Electric power generation in the Russian Federation by power plant type (1985–2020).

cator of 128.9 bln kWh, exceeding the level of 1989, which for a long time had remained a record, 128 bln kWh. State nuclear power was the first industry in Russia to restore its potential after a crushing drop in all economic indicators in the 1990s. For the oil industry, the production of metals, and other industries that fell into private hands, it took another 5–10 years. Under stagnation of the economy, which led to a lack of demand for the development of electricity production, nuclear power increased electricity production to 215.7 bln kWh in 2020. Power generation by nuclear power plants in the European part of the country reached almost 40%.

The industry's products are a key part of high-tech exports: the ten-year portfolio of overseas orders of Rosatom exceeds $130 bln, while, for example, the similar arms export portfolio is about $50 bln. The leading positions of Russia are achieved in tough competition with the United States, France, Japan, and Canada. At the same time, new players from China and South Korea are actively advancing to world markets, offering similar products at a lower price and

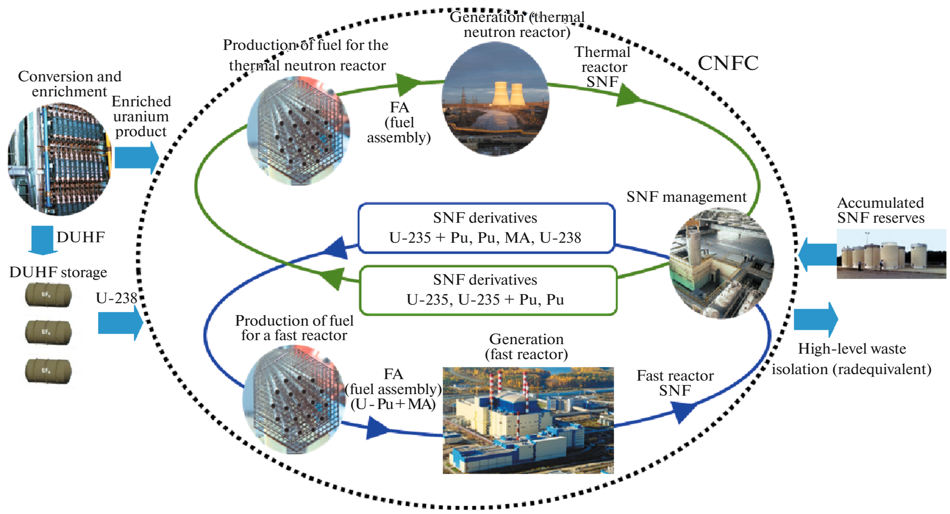

Fig. 6. Bicomponent nuclear power engineering (system of fast reactors and thermal reactors).

accompanying their offers with cheap loans. In these conditions, maintaining world leadership is impossible without developing new technologies and solving the systemic problems of nuclear power, which include the following:

• severe accidents—refusal of Germany, Switzerland, Belgium, and, possibly, South Korea to use nuclear power;

• low efficiency of using the extracted natural uranium raw materials—0.7% (^{235}U content);

• deferred problem of spent nuclear fuel (SNF)—accumulation and lack of environmentally acceptable handling of long-lived high-level waste, minor actinides, etc.;

• the risk of diversion of fissile material circulating in the nuclear fuel cycle for military or terrorist purposes;

• the danger of losing competitiveness.

The development of a new technological platform for nuclear power was initiated by the federal target program adopted by the government of the Russian Federation in 2010, within the framework of which the "Proryv" ("Breakthrough") project was formed in 2012 [1]. The purpose of this project is to build, along with the technologies of the existing nuclear power, which thus far has used an open nuclear fuel cycle and thermal reactors, a new branch of nuclear power based on fast reactors with a closed nuclear fuel cycle (Fig. 6). We view bicomponent nuclear power as the main nuclear technology in this century. Its development will reduce the accumulation of spent nuclear fuel, decrease the volume of radioactive waste, increase the efficiency of the use of uranium raw materials and environmental performance, and maintain the competitiveness of nuclear energy in comparison with other generations [2].

For the main water-moderated power reactor (VVER) technology currently in use, two stages of development are envisaged. The first one is VVER-S with spectral regulation and control by changing the water–uranium ratio when using propellers during the fuel campaign. Such reactors make it possible to increase the Pu production factor to 0.7, to reduce the consumption of natural uranium by about 30%, to load the core fully with mixed uranium–plutonium fuel, and by eliminating the special vessel required for boron regulation and some technological systems, to reduce capital costs by 10–15%. The elimination of Zr as a material for the cladding of fuel elements removes the problem of hydrogen explosions like those that took place at the reactors of the Fukushima-1 NPP.

At the second stage—VVER-SKD (supercritical water-cooled reactors)—a transition to a fast neutron spectrum and achievement, as in all such reactors, of self-sufficiency in fuel (BR ~1 instead of 0.3–0.5) are envisaged. The thermal parameters, including an efficiency of ~46% instead of 36% in NPP-2006, are aligned with the characteristics of modern thermal power engineering. The introduction of the considered improvements of the VVER technology is associated with solution of the problems of materials science.

The prospects for fast reactors and their supposed safety advantages are associated with the above-mentioned designs of integral reactors, the body of which concentrates all the elements of the primary circuit, steam generators, and emergency heat removal systems. The structural design, once proposed by Dollezhal', excludes losses of the coolant and heat removal from the core, which deterministically eliminates the likelihood of severe accidents, such as at the Three Mile Island Nuclear Generating Station (United States, 1979) and Fukushima-1 (Japan, 2011). To exclude the likelihood of a reactivity accident like the

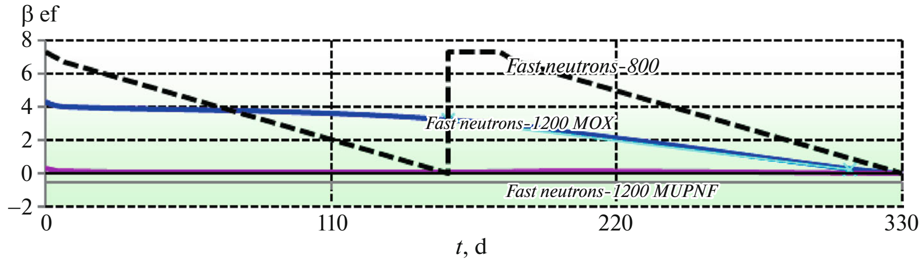

Fig. 7. Course of reactivity for a campaign in a BN-1200 reactor using oxide (MOX) and nitride (MNUP) fuel.

one that took place at the Chernobyl NPP in 1986, it is proposed to use an equilibrium fuel, which makes it possible to avoid an excess reactivity margin in the reactor facility and, therefore, to exclude deterministically such an accident as well. The equilibrium fuel evens out the combustion of some isotopes (U or Pu) and the production of plutonium, which makes it possible to assume that any theoretically possible accidents will proceed without the need to evacuate and, moreover, to resettle the population living near the station, as well as to withdraw large land areas from the economic circulation and, consequently, without major economic damage [3].

Such fuel could be a mixed nitride U–Pu fuel (MNUP), the leadership of which in the development of this technology and substantiation of its efficiency during reactor tests (up to 9% of the burnup of heavy atoms) belongs to Russia. Figure 7 shows the course of reactivity for a campaign in the BN-1200 reactor using oxide (MOX) fuel and MNUP. The advantage of the denser and more heat conducting MNUP is obvious [4].

Closing the nuclear fuel cycle allows, through the transmutation of the most long-lived isotopes, implementation of the so-called radiation-equilibrium management of radioactive waste, in which after 300–500 years, depending on the degree of purification from minor actinides, the radiation equilibrium of the extracted uranium raw material and the buried waste is achieved. With all the details of this approach discussed by specialists, it is obvious that the argument about preserving the Earth's radiation balance unchanged may turn out to be decisive for public recognition of nuclear power as a key one among other "green" generations [5].

Russia won the competition with France in the consistent development of a line of fast neutron reactors (FNRs): from BR-5 in 1959 to BN-800 in 2015, consistently increasing capacity and mastering the physics of FNRs and sodium coolant technologies. Thanks to this, the Russian Federation remains the world's leader in the field of FNRs, in which China and India are now actively involved.

Keeping the best achievements in the field of FNRs with a sodium coolant and oxide fuel, Russia has seized leadership from the American electrical engineering company Westinghouse, which has designed or licensed most of the world's nuclear power plants. In 2015, Westinghouse announced that the next generation of reactor facilities would be FNRs, and not with metallic fuel, which the United States for many years had considered as promising for fast reactors, but with MNUP fuel, as well as with a lead coolant. Except for the metal–concrete body, which our competitors did not dare use, these are the same constructive approaches as in the domestic development of the BREST reactor (Fig. 8), which allows us to speak about the interception of the American leadership in the development of a new technological platform for nuclear power. A pilot demonstration complex, including a fuel production facility, a BREST-OD-300 power unit, and an SNF reprocessing module corresponding to the approaches of the new technological platform is being built at the site of the Siberian Chemical Combine: from the first Siberian NPP to an advanced NPP with a station-based closed nuclear fuel cycle (CNFC).

The economy of nuclear energy has always been distinguished by high capital intensity, but it won in the cost of electricity and heat produced, since, unlike organic generation, its fuel component is several times lower. Design changes determined by safety requirements after severe accidents have put nuclear power on the brink of competitiveness. New projects of nuclear power plants with thermal and fast reactors can remain competitive with the currently main competitors (combined-cycle plants), provided that the price of money is not too high. Thus, at a zero-discount rate, LCOE[1] NPPs of any type are highly competitive (Fig. 9) and remain such at a discount rate of about 5%. For all capital-intensive objects in the world, there are no significant requirements for the value of money, and it is clear that the state wins by providing budgetary money or money from the Russian National Welfare Fund for the construction of nuclear power plants in Russia or abroad, compared to placing it in American or European public securities [6].

[1] LCOE (Levelized Cost of Energy) is the average estimated cost of electricity generation over the entire life cycle of a power plant, including all possible investments, costs, and revenues.

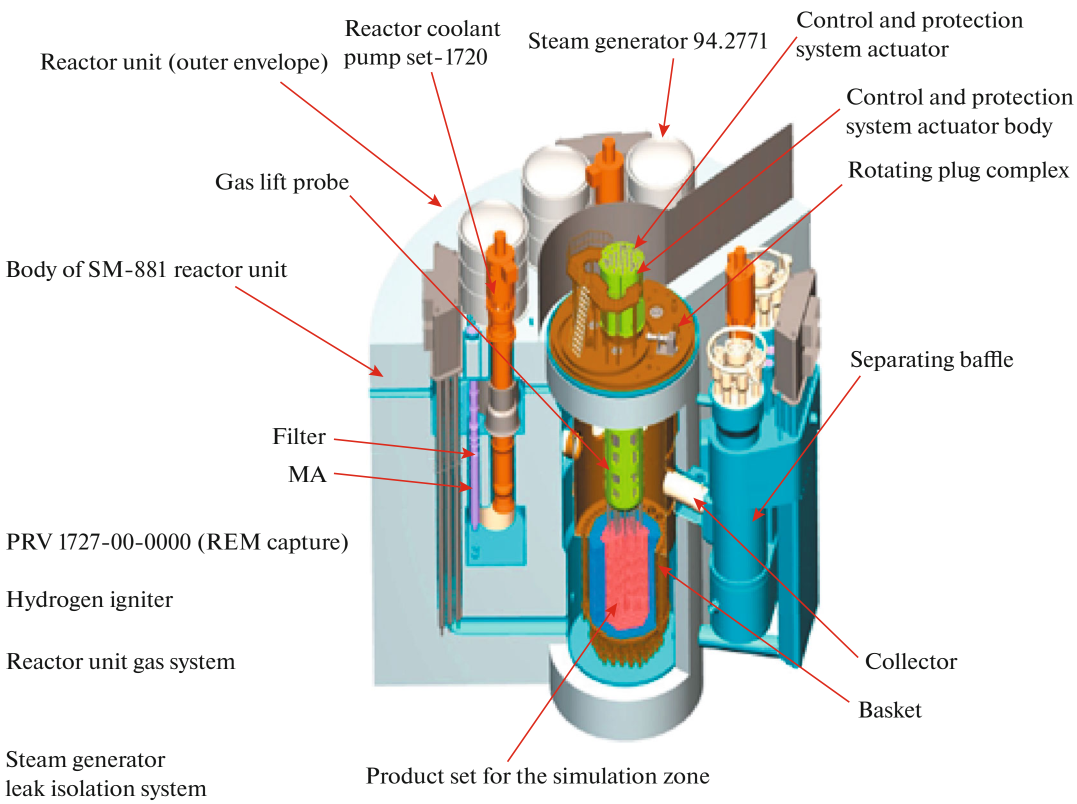

Fig. 8. Reactor installation BREST-OD-300.

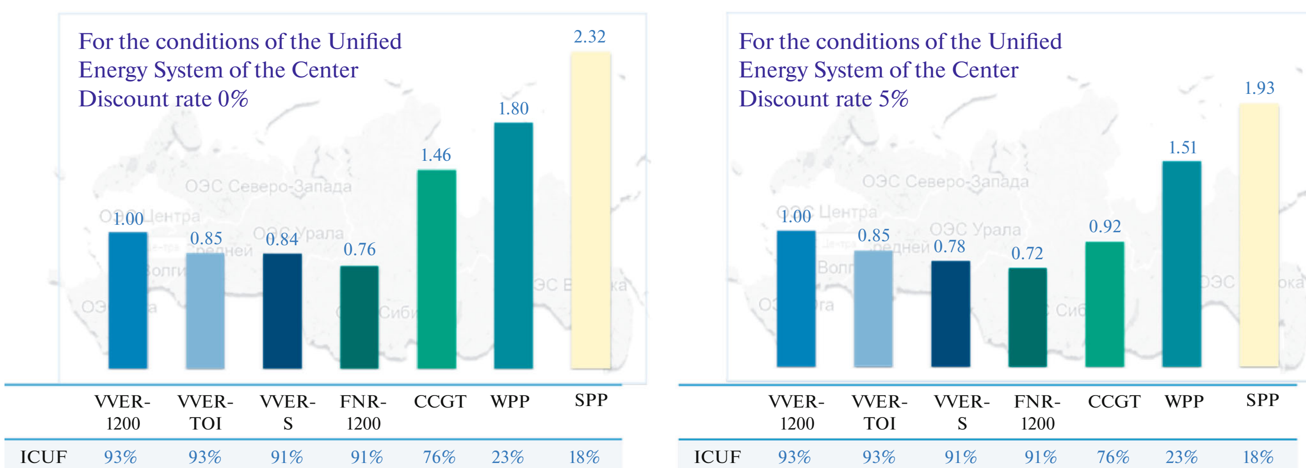

Fig. 9. Potential for ensuring the competitiveness of bicomponent nuclear power—LCOE of energy technologies, rel. units.

When developing objects of nuclear power and the nuclear fuel cycle, methods of computer calculation and modeling are actively used. The initial basis for such calculations was mainly made up of software developed at the Keldysh Institute of Applied Mathematics of the USSR Academy of Sciences and the Leipunskii Institute of Physics and Power Engineering under the leadership of Academician G.I. Marchuk, while at present the leader of such developments is the RAS Nuclear Safety Institute under the leadership of Academician L.A. Bol'shov, combining the results of both its own specialists and those of other institutes of the Russian Academy of Sciences, Rosatom, and universities. Initially, all programs were envisaged exclu-

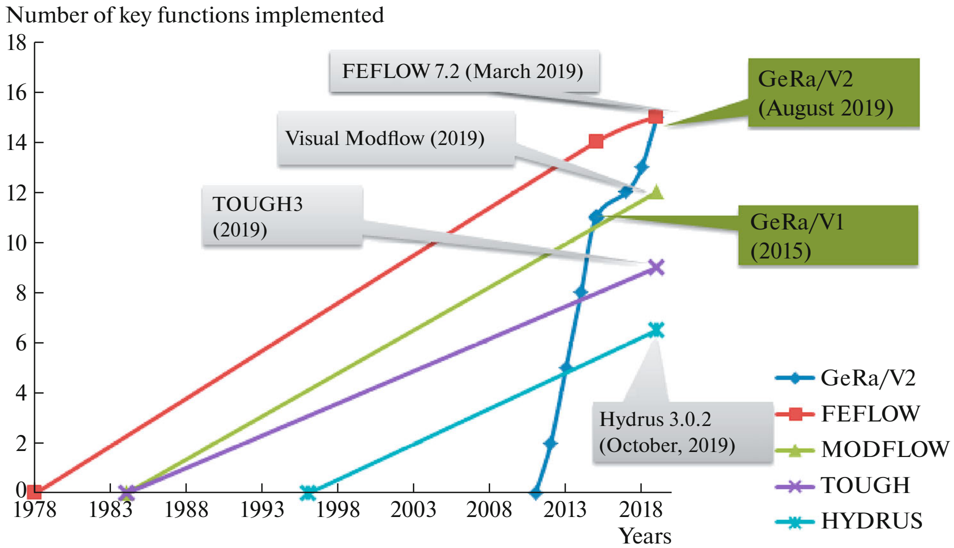

Fig. 10. The pace of development of the GeRa code in comparison with foreign counterparts.

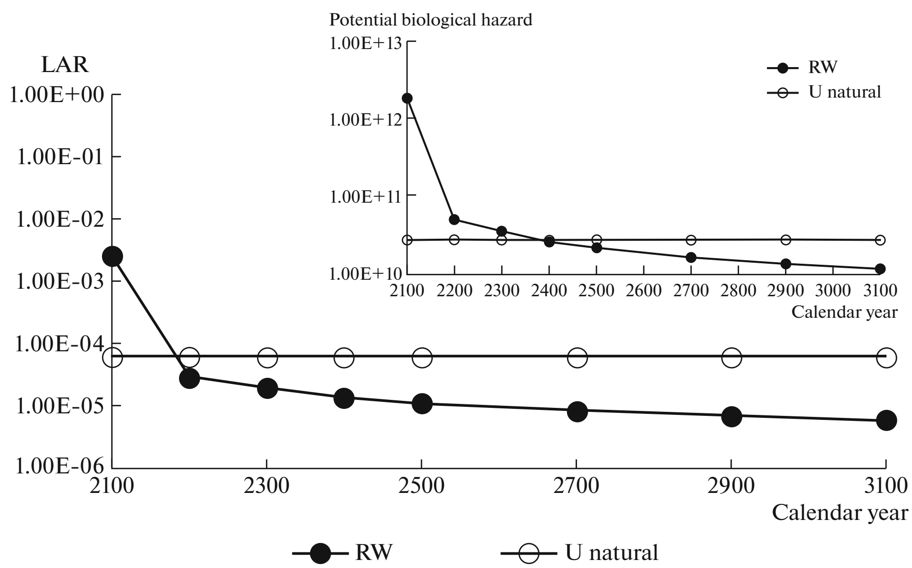

Fig. 11. Radiological equivalence in terms of carcinogenic risk is achieved after 100 years of exposure.

sively for reactor facilities, while in recent years codes have been created to solve problems of the nuclear fuel cycle. Comparison of the codes (Fig. 10) shows both a greater accuracy of domestic developments and a significantly shorter time necessary to create import-substituting codes. The Russian code "Nostradamus" has demonstrated excellent results in predicting the transport of radioactivity in the atmosphere from the Fukushima site during the accident at the Japanese nuclear power plant in 2011 to the East European part of Russia [7].

The much talked-about digitalization has been taking root in the development of nuclear facilities since the 1950s, from the use of keyboards to today's powerful computers. The entire path from R&D to the decommissioning of nuclear power facilities is accompanied by the creation of digital twins and the simulation of their operation under normal operating conditions and deviations from them, up to the postulation of severe accidents.

A unique achievement of academic science was the addition to the substantiation of radiation-equivalent radioactive waste management, which was discussed

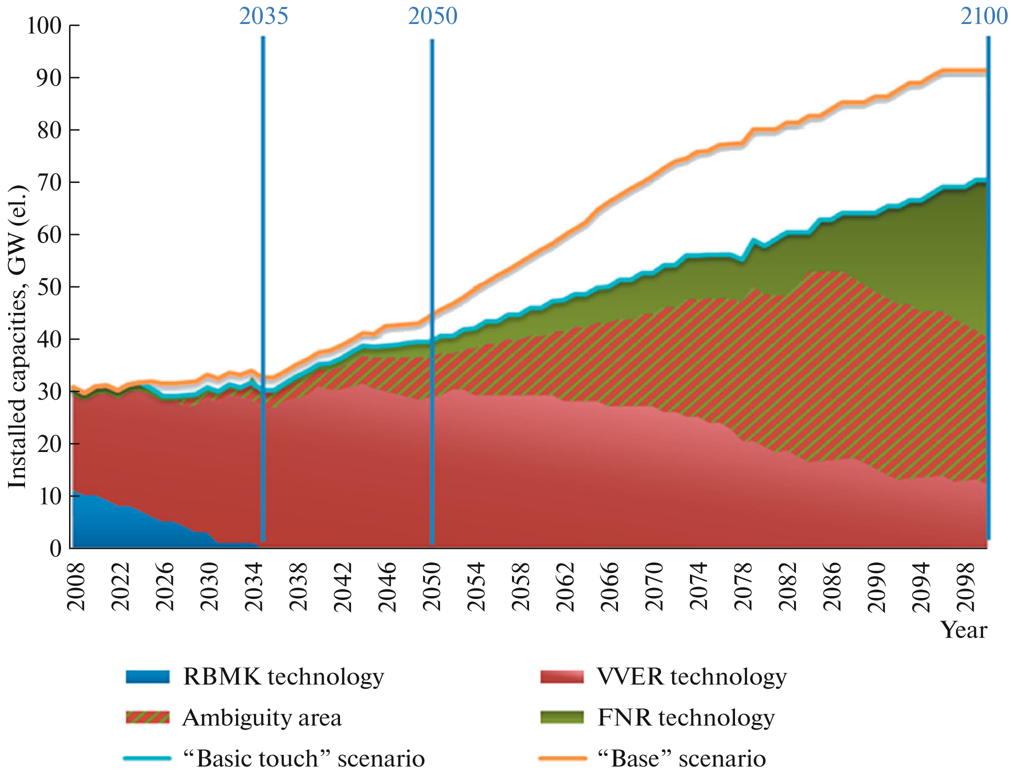

Fig. 12. Options of scenarios for the development of nuclear power.

above. Under the leadership of RAS Corresponding Member V.K. Ivanov, it has been shown that cancer equilibrium, i.e., the risk of cancer from radioactive waste and uranium raw materials, is achieved even faster, after about 100 years, under a closed nuclear fuel cycle (Fig. 11) [8].

At the end of 2018, the Presidium of Rosatom's Scientific and Technical Council approved the Strategy for the Development of Nuclear Power Engineering, which provides for an NPP capacity in the range of 70–90 GW by the end of the century (Fig. 12). The zone of ambiguity is due to the fact that not all theorems of the advantages of FNRs have been proven thus far and, perhaps, with a delay in this, the main load will have to be taken on by thermal neutron reactors with the improvements discussed above. In any case, it is already obvious that nuclear power, free of the previously listed problems, can become the basic element of clean energy, the main element of the "green square," the other sides of which are hydropower, wind, and solar power [9].

We expect that, as in previous years, the development of nuclear power will proceed in close cooperation between Rosatom, the Russian Academy of Sciences, and the NRC Kurchatov Institute.

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