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TWO-COMPONENT NUCLEAR POWER SYSTEM WITH A CLOSED NUCLEAR FUEL CYCLE BASED ON BN AND VVER REACTORS

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The results of a comparative analysis of the materials and technical-economic indices of a nuclear power system with open and closed fuel cycles are presented. A full account is given of the validation and the conditions for transitioning to a two-component nuclear power system with a closed nuclear fuel cycle with thermal and fast reactors.

The results of a comparative analysis of the materials and technical-economic indices of a nuclear power system with open and closed fuel cycles are given in this article. The validation and conditions for transitioning to a two-component nuclear power system with a closed nuclear fuel cycle with thermal and fast reactors are given. A detailed exposition of the method of analysis, the initial data, and the results is given in [1].

Initial Provisions

Contemporary nuclear power, which is based on many years of experience in designing and operating thermal reactors, demonstrates stable positions satisfying the requirements of safety and economics. Thermal reactors operate in an open fuel cycle, and the natural uranium resources and generation capacities of the fuel cycle are sufficient for the present volume of power generation. The growth of nuclear capacity in the country and in the external market requires that nuclear power become more competitive in terms of capital and operational costs and it will depend on the solution of the problems of managing spent nuclear fuels and wastes and how efficiently the energy potential of natural uranium is used. The growing volume of spent nuclear fuel in the established approaches to price formation even at the nearest stage is becoming an appreciable economic burden of the power-generating complex. The anticipated increase in the nuclear generating capacities in the country and abroad will inevitably lead to high market prices for natural uranium and will make it necessary to increase its burn efficiency.

A radical solution of the problems of managing spent fuel and radioactive wastes and supplying nuclear power with actually unlimited resources of nuclear fuel lies ahead on the path to a two-component nuclear power system with a closed nuclear fuel system and a close nuclear fuel cycle with thermal and fast reactors [2]. A two-component nuclear power system includes NPP with thermal and fast reactors and the enterprises of a centralized nuclear fuel cycle (NFC). NPPs generate power and breed fuel. The NFC enterprises promote NFC closure, including spent fuel storage and reprocessing, fabrication of fuel for the initial load and refueling of the reactors, multiple recycling of the regenerated plutonium and uranium, and waste conditioning and isolation. The initial load of the fast reactors consists of plutonium obtained by reprocessing the spent fuel from thermal reactors. Plutonium obtained by reprocessing the spent fuel from thermal reactors and from the fast reactors themselves is used to refuel the fast reactors. The thermal reactors operate on uranium fuel and partially mixed uranium-plutonium

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oxide fuel fabricated from the fast-reactor plutonium. Together with reactor plutonium, a two-component system also uses the plutonium extracted from the weapons arsenal.

The formation of such a nuclear power system is based on the experience existing in contemporary nuclear power with VVER and the technological know-how already accumulated on fast sodium reactors, reprocessing of spent fuel, recycling uranium, and waste management. NPPs with VVER that are currently operating or under construction, taking account of their assigned service life and improvements, will make the main contribution over the course of many decades to the production of nuclear power in Russia and nuclear exports. The highest priority is guaranteed nuclear and radiation safety for all elements at all life-cycle stages of the nuclear power system formed.

Sodium-cooled fast reactors. These reactors were developed and adopted in Russia starting in the mid-1990s [3, 4]. Fast reactors come with commercial operating experience and their technical-economic characteristics can be acceptable. A key index of their attractiveness for adoption in a two-component nuclear power system with a closed fuel cycle is the fuel breeding ratio (BR). Its numerical value depends on the nuclear material and neutron spectrum in the reactor. The path to high breeding is a reactor with a fast neutron spectrum, using plutonium as the fissile material and ^{238}U as the raw material. The number of neutron-moderating light nuclei must be reduced in the core of a fast reactor – in the fuel, structural materials, and coolant. Investigations performed on BR-1 and subsequent experiments on BR-2, -3, and -5 showed that high BR (BR > 2) can be attained in compact plutonium reactors with a high-energy neutron spectrum. The aims of NFC closure and the adoption of fast reactors are not only to increase the usage efficiency of natural uranium by breeding and recycling plutonium but also to solve the problems of safe management of radioactive fission products and transuranium isotopes.

The question of the choice of coolant for a fast reactor was initially solved in favor of molten sodium. The other liquid metals – mercury, lead, and lead-bismuth alloy – were rejected for nuclear-physical reasons and because of their thermohydraulic and physicochemical properties. Nonetheless, in searching for ways to improve fuel breeding and increasing safety attention was repeatedly turned in subsequent years in the country and the world to research and development work on fast reactors with lead and helium coolant. Fast sodium reactors dominated. The experimental BOR-60 reactor was built and is now operating. The No. 3 unit of the Beloyarskaya NPP with BN-600 has been operating successfully for more than 30 years and power startup of the No. 4 unit with BN-800 is being conducted. The technical decisions tested in BN-600 and -800 are used in the development of an innovative design of the head commercial power-generating unit with BN-1200.

Two fuel variants are under development in Russia for fast reactors: mixed uranium-plutonium oxide and nitride fuels. Research is also being done abroad on mixed metallic uranium-plutonium fuel. The mixed uranium-plutonium oxide fuel has a prepared technological base and burnup, power density, and breeding parameters that are acceptable for the initial stage of development. The mixed uranium-plutonium nitride fuel is under consideration for the future. Its main advantages are considered to be higher density in terms of heavy metals and smaller number of ancillary light atoms, which makes it possible to increase the breeding ratio in the core (BRC) to several units. For BRC ~ 1, the reactivity excess on burnup can be decreased, which simplifies the reactor's control and protection system. Nitride fuel possesses inherent characteristics which are impeding its use. The high swelling of the nitrides upon burnup and low plasticity compared with uranium-plutonium oxide fuel limit burnup, which is the key for determining the technical-economic indices of the fuel cycle. The use of mixed uranium-plutonium nitride fuel with lower burnup increases the materials flows in the fuel cycle, which increases the fuel component of the cost of electricity. In the near- and medium-range future, the construction of the two-component nuclear power system with a closed fuel cycle will be based on fast reactors with mixed uranium-plutonium oxide fuel. This choice takes account of the fact that in a two-component nuclear power system such fuel is used not only in fast reactors but also in VVER. Such fuel has been adopted abroad on a large scale for use in PWR.

Nuclear power in Russia. At present, it is impossible to predict the state of affairs in the global energy market in the next decade. But it can be supposed quite confidently that the energy market will not quiet down until the specific energy consumption in the developing world approaches the average world level. This means that two- or three-fold growth in global energy consumption can be expected at mid-century. As a traditional supplier of energy resources, Russia will participate in a competitive war for this market in terms of all types of energy resources. Moreover, this pertains to the nuclear market where with active advancement of new technologies Russia can claim a significant fraction of the market ~20%, which signifies approximate equality in the generating capacities inside the country and abroad. The construction of nuclear power-generating units inside the country is validated not only by the requirements of growth of the stabilizing link in power generation. Competitiveness in the external market must be confirmed by the presence of active base projects in the country and the presence of a corresponding infrastructure of the nuclear fuel cycle, machine engineering, metallurgy, materials science, geology, construction industry, electronics, education, science, and others. Strategically, it is wrong to adopt a decision concerning the fate of NPPs only on the basis of the criterion of immediate economic competitiveness with other sources of electricity, specifically, gas.

To realize the intentions of obtaining a stable position in the external nuclear market, activating suppliers with unlimited financial possibilities, Russia must offer a new product that differs fundamentally from the proposals made by competitors and requiring a long time to develop and master. The adoption of a closed NFC in Russia and fast reactors in a two-component nuclear power system will fundamentally improve the export potential of NPPs with VVER. The construction of NPPs with VVER in foreign countries takes on a new quality owing to the possibility of presenting a complete set of nuclear-fuel services, including delivery of fresh nuclear fuel and return of spent fuel over the entire NPP life cycle. In addition, the return of spent fuel from foreign NPPs built according to a domestic design is done not for eternal disposal but rather for reprocessing and effective burning of the regenerated fuel in fast reactors. The realization of this advantage is especially important for assimilating the market in developing countries, because it is too expensive to create an NFC in these countries.

Nuclear power development scenarios in Russia. In the research and comparative analysis of a nuclear power system with open and closed NFC, the following scenario was adopted for the development of nuclear power and the atomic energy and industrial complex of the country. The nuclear power and atomic energy indices are now known. At the stage up to 2035, the capacities will grow according to the target road map for commissioning and decommissioning installed capacities. The number of units commissioned at the end of this period equals two per year, which makes it possible to compensate the decommissioning of power units which have exhausted their service lives and growth of installed capacity. After 2035, this construction rate will be maintained – two power units per year; the power units are decommissioned at the exhaustion of the service life (60 yr). Under these assumptions, the installed electric capacity of NPP will equal about 70 GW by mid-century and about 140 GW by the end of the century. These figures include the installed capacity of the power units built in Russia and abroad according to domestic designs. It is anticipated that the production capacities of the domestic atomic energy and industrial complex support the construction of all these generating capacities and the complete complex of NFC services. The ratio of the power units built in this country and abroad is not constant in time; it depends on the market conditions and Russia's activity in the external market.

Mathematical models and software. An analysis of the indices of a nuclear power system with BN and VVER operating in open or closed nuclear fuel cycles was performed using the following software: DESAE-F (National Research Center Kurchatov Institute), CYCLE-M (Physics and Power Engineering Institute), and FIN-MODEL (All-Russia Research Institute of Nuclear Power Plants). Taken together, these software complexes make it possible to model the behavior of reactor fuel for uranium, uranium-plutonium, and uranium-thorium fuel cycles taking account of the changes in the isotopic composition of the uranium, plutonium, and transuranium isotopes during repeated passage of the nuclear materials through the fuel cycle. The technical and economic indices are calculated for the complete life-cycle interval of the power units and industrial objects of the NFC according to the following articles: receipts from electric sales, investments in construction and decommissioning, fuel component taking account of price escalation, and economic efficiency indices. In the course of the investigations, all three complexes were used; supplementing one another, they afforded completeness and increased the reliability of the results.

Initial data. The initial technical and economic data obtained on the basis of an analysis of the domestic and foreign information were used in the calculations. It can be stated that the accuracy of the physical and technical data on reactors was adequate for systems analysis. At the same time, there is significant variance in the data on the limits of the fuel cycle, which affects the reliability of the analysis. This concerns especially the cost of reprocessing and storage of spent fuel, fabrication of mixed fuel, and management of radioactive wastes.

Discounting. The discounting method was used to compare the economic indices of the development variants of the nuclear power system – calculation of the reduced money expenditures on the entire life cycle. Ordinarily, discounting is used to compare the economic attractiveness of similar projects. In this case, the long-time development strategy for a nuclear power system with open and closed NFC, based on projects with substantially differing technologies and levels of readiness, is compared. In addition, these technologies are realized at separate times of the stages of a long life cycle. These factors affect the reliability of the comparison. For a good assessment of the effect of these factors on the results of the analysis, the calculations were performed with different discount rates.

Analysis of a Two-Component Nuclear Power System

The question of an open or closed fuel cycle has been under discussion since the beginning of nuclear power. There are many yeses and nos for each of these avenues. The solution largely depends on the scale of nuclear power. For the current small scale of nuclear power in global energy production, in terms of uranium conservation the advantages of NFC closure and reduction of the spent fuel volumes can hardly play a determining role in establishing its priority. The foreseen inevitable growth of nuclear capacities, especially in countries with developing economies, exacerbates the solution of the problem of fuel reserves and the management of spent fuel and wastes. Developing countries aiming to use atomic energy will not be able to develop, at least initially, all components of the nuclear fuel cycle. This is for supplier countries. These circumstances must be taken into account in choosing scenarios for the development, formation of the structure, and planning of nuclear power and its atomic industrial complex.

The indices for nuclear power with open and closed NFC and VVER-TOI and BN-1200 power-generating units were compared in terms of two criteria: comparison of capital expenditures for the construction of NPPs and expenditures on fuel and waste management.

Comparison of capital intensiveness of NPPs with BN and VVER. A comparison showed that the specific capital costs of NPPs with BN-1200 exceeded the levels for NPPs with VVER-TOI by 10% with optimistic and up to 20% with a pessimistic evaluation. One reason for this difference is that the comparison was made using data from the BN-600 and -800 designs which were completed 20–30 years ago and were essentially prototypes aimed at the development of fast sodium reactors. On the basis of the comparison, measures were proposed for improving the design of the head power-generating unit with BN-1200, making it possible to decrease the capital component of the costs at least to the level of typical projects with VVER. These measures include reduction of the metal content and cubic capacity of the buildings, optimization of the structural and construction-technological solutions, the critical path for construction, measures to reduce the NPP construction times, and transitioning to assembly-line construction.

Cost of fuel and waste management. The operating costs of fuel and waste management for scenarios with open and closed fuel cycles were compared for different variants of management of spent fuel and wastes. An open nuclear fuel cycle is examined for three variants of spent fuel management: long-time storage, long-time storage + disposal from 2030, long-time storage + reprocessing from 2030 + waste disposal + long-time storage of reactor plutonium. The following data were used in the calculation of the costs of the fuel component: cost of storage – 5 $/kg/yr, cost of reprocessing – 600 $/kg, cost of plutonium storage – 2 $/g/yr, and cost of spent fuel storage for 40 yr followed by shipment, encapsulation, and disposal – 850 $/kg. Under these conditions, the variant with long-time storage shows the lowest minimum total cost. An open cycle with reprocessing of spent fuel but without recycling of plutonium shows considerable higher total cost, since in the cost balance the reduction in the volume of the stored spent fuel competes with the increase in the cost of reprocessing and waste management and, more importantly, the cost of storing the separated plutonium.

The fuel component of the costs in a nuclear power system with a closed NFC was analyzed with variation of the ratio of fast and thermal reactors and with the same total capacity for each variant. In a two-component nuclear power system with fast and thermal reactors, the total cost of fuel changes for opposite reasons. The costs decrease owing to their reduction for natural uranium and its enrichment in connection with a reduction of the VVER fraction in the structure of the generating capacities and because of the volume reduction owing to reprocessing of spent fuel in repositories and because of reduction in the warehoused plutonium volume in connection with continuous use in fast reactors and, when necessary, in VVER. This is countered by the cost of reprocessing spent fuel and higher cost of production with recycling of plutonium and uranium. Ultimately, the data used for the retooling costs give the advantage to a closed cycle. These advantages are already evident for a relatively low fraction of fast reactors in the structure. These advantages become more clearly evident as the fast-reactor fraction increases. At the same time, because of the significant duration of the technological processes of the nuclear fuel cycle – irradiation of the fuel in a reactor, storage of spent fuel, reprocessing, and fuel production – the advantage of closing the NFC is delayed. The effect due to NFC closure and the adoption of fast reactors is fully manifested in a time comparable to the life cycle of an NPP power-generating unit.

Uranium price escalation. The rate of escalation of uranium prices is of fundamental importance in comparing the economic indices of the variants with open and closed fuel cycles. The fuel component of the costs for BN-1200 does not depend on the uranium price escalation, while for VVER it increases appreciably. In this connection, the competitiveness of BN-1200 will increase with increasing cost of natural uranium. For uranium price escalation of 2%/yr, the difference in the total fuel costs between an open cycle based on VVER and a closed cycle with BN/VVER ratio 1/1 equals about 15% in favor of the closed cycle.

Repeated recycling of fuel. In closing the NFC, the isotopic composition of the plutonium formed during repeated recycling of fuel is of fundamental importance. The neutron spectrum of a fast reactor promotes the formation and maintenance of satisfactory quality of the isotopic composition of the plutonium as well as the plutonium from thermal reactors that is used for the initial load and makeup. The particularities of the neutron spectrum of a thermal reactor promote the production of plutonium with a worse isotopic composition than in fast reactors, and upon recycling of this plutonium in thermal reactor the isotopic quality degrades. In a fast reactor with recycling of plutonium loaded from thermal reactors, the isotopic quality improves. Thus, a two-component nuclear power system with fast and thermal reactors and a closed fuel cycle promotes repeated recycling of plutonium. Any attempt to solve the problem of the accumulation of spent fuel by closure of the fuel cycle in a single-component structure with VVER will encounter quality degradation of the plutonium upon repeated recycling. In the future, thermal reactors in a two-component structure can use low-background plutonium produced in fast reactors, compensating the growing deficit of cheap natural uranium.

Structure of a two-component nuclear power system with a closed NFC. The equilibrium ratio of fast and thermal reactors with prescribed characteristics is determined under an additional condition – no accumulation of warehoused spent fuel and plutonium. In the equilibrium system, 2/3 consists of VVER with partial (0.4) loading of the core with mixed uranium-plutonium oxide fuel and 1/3 consists of BN-1200 fast reactors; the consumption of natural uranium and the separation operation in such a system decrease 2.5-fold compared with the analogous characteristics for a system consisting of VVER in an open cycle.

Effect of new technologies on the indices of a two-component nuclear power system. In estimating its development in the long-time future, it is necessary to evaluate the effect on the final results of new technologies with improved parameters of fuel use and capital costs (index C). The improvement of fuel usage is characterized as follows: for BN-C, the specific plutonium load decreases to 4 tons/(GW·yr) compared with the adopted value ~6.2 tons/(GW·yr) and an increase of the BR to 1.4 compared with 1.2; for VVER-C, the consumption of natural uranium decreases to 130 tons/(GW·yr) compared with ~160 tons/(GW·yr) and the BR increases to 0.8 compared with the average BR ~ 0.5 (for fuel assemblies BR ~ 0.7 with mixed uranium-plutonium oxide fuel and BR ~ 0.35 with uranium fuel). An increase of the BR and a reduction in the specific load in a fast reactor makes it possible to increase the capacity growth rate. Moreover, the excess plutonium can be used to replace the uranium fuel in VVER with mixed uranium-plutonium oxide fuel and, correspondingly, to reduce the demand for natural uranium. At the same time, the total cost of fuel changed very little. This is explained by the relatively high cost of fabrication of mixed fuel for the assigned initial cost data for VVER-C fuel assemblies. In this connection, together with the work on improving the characteristics of BN-C and VVER-C, it is necessary to step up work on perfecting and improving the technical and economic indices of fuel cycle retooling for reprocessing spent fuel and fabricating mixed uranium-plutonium fuel.

The key avenue for making nuclear power more competitive as compared with power-generation based on fossil fuels is reduction of the capital and operating costs. Works on reducing the capital inputs have been formulated and are being conducted for NPPs with VVER-TOI. Design solutions and solutions in the construction sphere, which were aimed at reaching specific costs comparable to the level for serial VVER, are being worked out for NPPs with fast reactors. These solutions must be implemented in the construction of the head unit BN-1200. In determining the maximum competitive cost of capital investments in NPPs as compared with thermal power plants (TPP) based on steam-gas combined cycle plants (CCP), several factors must be taken into account. The price difference of internal and external gas places the solution of the problem of the advantage of generating capacities of one or another type outside the sphere of economics proper. Taking account of the price dynamics on fossil fuels and the dependence of the Russian economy on this, it is incorrect to determine the maximum cost of capital investments in NPPs as compared with CCP under conditions of critical price instability. In a crisis and with economic sanctions, the capital component (partially) and the operational TPP with CCP are sensitive to the exchange rate because of the significant fraction of imported equipment in CCP. Finally, in making comparisons the CO_2 emissions must be taken into account in the cost of the energy produced.

Two-product model. Nuclear power plants with fast reactors produce, together with energy, a new nuclear fuel, which after reprocessing of the spent fuel is returned into the same and other fast reactors as well as into thermal reactors. Calculations of the material balances in such a two-product system do not present any difficulties. Estimates of the economic efficiency must take account of the production of two products: energy and fuel. The contribution of the energy and fuel produced in a reactor to the economic indices of NPP depend on the market conditions and determines the choice of parameters and operating regimes of the reactor and fuel cycle. The construction of an economic model of a two-product nuclear energy system strongly depends on the interaction of the main participants of this process and their configuration. It can be supposed that the government corporation Rosatom implements the two-product model with the lowest cross-boundary losses.

Formation and Development of a Two-Component Nuclear Power System with a Closed NFC

The results of a comparative analysis of the material and the technical and economic indices of a nuclear power system with an open or closed fuel cycle were used in the preparation of the formation and development of a two-component nuclear power system with a closed nuclear fuel cycle with BN and VVER reactors during the nearest quarter of the 21st century.

Initial state. Nuclear power plants with VVER, RBMK, and BN (BN-600 and BN-800) reactors are in operation. In accordance with the technical regulations, work is being conducted on service-life extension and decommissioning procedures.

Formation of a two-component nuclear power system with a closed NFC. In the main, power-generating units with VVER are being built in Russia and abroad. The rate of construction is determined by the replacement of decommissioned power units and the internal and external market conditions. The growth of installed capacity corresponds to the active road map for the introduction of generating capacities with partial replacement of VVER-1200 by fast reactors (head series). The development of the BN-1200 design and the materials for a BN-1200 power unit will be completed in 2016. In the road map up to 2035, three power-generating units with BN-1200 will be constructed: the head industrial unit No. 5 at the Beloyarskaya NPP, in the mid-2020s; and two typical commercial power units on the site of the Southern Urals NPP, in first half of the 2030s.

A commercial power generating complex that functionally combines a unit with BN-1200 and plants in a centralized closed NFC is under consideration as the base element of a two-component system with a closed NFC with BN-1200 and VVER-TOI. The plants giving closure of the BN-1200 fuel cycle operate in the structure of a centralized closed fuel cycle. The centralized closed NFC combines technologically coupled clusters of the NFC with BN and VVER, including temporary storage and reprocessing of their spent fuel, the production and exchange of regenerated plutonium and uranium, fabrication of mixed uranium-plutonium oxide fuel for them, and reprocessing and preparation of types of wastes for isolation.

The base technologies for closing the nuclear fuel cycle are being worked out during the operation of the No. 3 unit (BN-600) and the No. 4 unit (BN-800) at the Beloyarskaya NPP in combination with the existing and newly developed plants for fuel fabrication, reprocessing of spent fuel, and management of spent fuel and wastes (Industrial Association Mayak, Mining and Chemical Combine, Siberian Chemical Combine). Commercial production of mixed uranium-plutonium oxide fuel for BN-800 started at the Mining and Chemical Combine in 2014. The No. 4 unit of the Beloyarskaya NPP with BN-800 is in testing operation at the capacity assimilation stage. The commissioning of a power-generating unit is an important milestone in the organization of a closed NFC. The BN-800, operating in the electricity production regime, will be fully used for implementing the scientific and technical programs on pilot-plant testing of nuclear fuel cycle closure technologies. Scientific and technical programs aimed at the following have been developed: assimilating a 100% core load of mixed uranium-plutonium oxide fuel, reducing the specific consumption on nuclear fuel from fast reactors by increasing its burnup and the run time of the fuel assemblies, preparation of the infrastructure for handling spent fuel for reprocessing mixed oxide fuel on a commercial scale, working out innovative technologies for a closed nuclear fuel cycle with fast reactors, testing mixed uranium-plutonium nitride fuel, and investigation of the technology for burning transuranium isotopes.

Development of a two-component nuclear power system with a closed NFC. In the third decade of the 21st century and beyond, generating capacities are being built in Russia and abroad at the rate of two power-generating units per year using Russian designs. Units with thermal and fast reactors are being built. The growth of installed capacity corresponds to the active road map for commissioning generating capacities but with partial replacement of VVER-1200 by BN-1200 (head series). The production capacity of the atomic energy and industrial complex permits the construction of generating capacities and a complete complex of NFC services including the delivery of fresh fuel and reprocessing of spent fuel, recycling of uranium and plutonium, and waste management. Fast reactors use mixed uranium-plutonium oxide fuel with plutonium obtained by reprocessing spent fuel from VVER and BN. Uranium oxide fuel is loaded into VVER. Depending on the conditions of the uranium market, VVER can use part of the load of mixed fuel with plutonium obtained by reprocessing spent fuel from BN. Russian designed NPPs are built in Russia and abroad in the approximate ratio 1/1. The ratio depends on the conditions of the oil and gas market. Power units with VVER with a complete set of fuel services are sent to the foreign market. The solution concerning foreign deliveries of NPPs with fast reactors must be checked from the nonproliferation standpoint. A necessary condition for deliveries of new-generation power units abroad is the confirmation of their operating parameters on units built in Russia.

Conclusion

A radical solution of the systems problems of today's nuclear power with an open fuel cycle – the growing accumulation of spent fuel and wastes and the low usage efficiency of natural uranium – lies in the way of forming a two-component nuclear power system with a closed fuel cycle with thermal and fast reactors. A two-component nuclear power system includes NPP with thermal and fast reactors, which generate energy and breed fuel, and a centralized closed nuclear fuel cycle which permits reprocessing of spent fuel, repeated recycling of fuel, and conditioning and isolation of wastes. A new technological system of resource-independent power generation is developed on this path; it will provide energy security for the country under the conditions of growing limits of raw materials.

Russia is best prepared technologically and organizationally to implement a two-component nuclear power system with NFC closure. The adoption of a closed NFC and fast reactors will confer competitive advantages in the external market. The construction of NPPs with VVER abroad acquires a new quality owing to the possibility of providing a complete suite of services for nuclear fuel, including delivery of fresh nuclear fuel and return of spent fuel during the entire life cycle of an NPP. In addition, the return of spent fuel from NPP built in foreign countries according to domestic designs is done not for disposal but rather for reprocessing and effective burning of the regenerated fuel in fast reactors in Russia.

The development of a technological platform for resource-independent power generation is stimulating expansion of applications of atomic energy in replacing fossil fuels in industry, housing and communal services, and transportation. This is the next technological regime – nuclear–hydrogen energy, where nuclear power plants will produce electricity, nuclear fuel, and hydrogen [5].

The combination of development and implementation of new nuclear technologies is one of a few available choices that will make it possible for the country to meet technological milestones that fundamentally alter economic development in the direction of stable development.

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