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SOME ASPECTS OF NUCLEAR POWER DEVELOPMENT IN RUSSIA AND STUDIES ON ITS OPTIMAL LONG TERM STRUCTURE

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Abstract

The paper presents the authors' outlook for nuclear power development in Russia. The analysis is based on the documents published and other materials as well as on the experience of the authors who participated in working out the state fuel-power program Power Strategy of Russia. The crucial point of the Strategy is that moratorium on the nuclear power development in Russia is inadmissible and a part of electricity production in the country will be covered by NPPs with increased safety. The studies which have been carried out by the organizations of MINATOM and ROSENERGOATOM and by some authors have shown that a potential of the Russia nuclear power complex meets the requirements of the nuclear power development up to year 2010. From the standpoint of the authors of the paper the investment climate in the country is the most important and uncertain factor influencing the program realization. But nuclear power preserves competitive ability in any option of new electric capacities introduced in Russia. Application of the market-oriented IAEA's planning tools have confirmed the competitive ability of nuclear power in the central region of Russia. This study is to be continued for other Russian regions. The estimates of the long-term prospects of nuclear power development in Russia made by the authors are based on the assumptions of natural uranium resources conservation, plutonium stockpile minimization and reduction of the radiotoxical waste to the lowest possible level. These requirements may be answered in the plutonium balanced system of thermal and fast reactors with a very economical consumption of natural uranium and a very small quantity of radioactive waste (mainly consisting of fission products and losses in reprocessing operations).

1. STATUS OF THE NUCLEAR POWER IN RUSSIA AND PRIORITIES OF ITS DEVELOPMENT

Russia has nine operating NPPs (29 units) with a total installed capacity of ~ 21.2 GWe. The 29 nuclear units in operation include: 13 with WWER PWRs (six WWER-440 and seven WWER-1000); 11 RBMK LWGRs; four EGP units of Bilibino NPP with channel water-graphite reactors; one fast neutron reactor BN-600. The contribution of nuclear power to the total electricity production in Russia is about 12% (more than 40% in some regions of the European part of Russia). All Russian nuclear units including fast neutron reactor BN-600 operate using uranium fuel. Annual spent fuel discharge amounts are about 800 t which contains about 4 t of plutonium and 0.3 t of minor actinides.

The fundamental directions of the nuclear power development in the country are determined in the **Power Strategy of Russia [1]** approved by the Government of the Russian Federation. The crucial point of the document is that a moratorium on nuclear power development in Russia is inadmissible and a part of the future electricity consumption will be covered by NPPs. Russia's decreasing oil and coal production - and the inevitable depletion of reserves of these fuels means that nuclear is one of the main guarantees of power supply security. The North-Western, Central and Northern Caucasus regions of Russia are the most suitable sites for NPPs.

The Power Strategy of Russia emphasizes the two principal stages of the Russian nuclear strategy:

1. Backfitting of existing nuclear power capacities through the next 10 to 15 years, completing the NPPs now under construction, developing and realizing designs of new-generation NPPs with increased safety;

2. Creating, in the nearest perspective, the preconditions for a considerable future increase of nuclear's contribution to the country's fuel balance ; and creating the base for a large-scale development of nuclear power after 2010 to generate up to 30-35% of Russia's total electricity generation and up to 40-50 % in the country's European part.

Realization of all the above stages will enable to [2]:

- diversify power production in the country and to provide economy of fuel and power resources to ensure their necessary export;
- create real conditions for increase of electricity export among European countries;
- create the base for easing Russian and European air pollution, e.g., the ecological policy stipulated by the **Power Strategy of Russia** aims at reducing the technological impact of fuel and power on the environment;
- solve the problem of utilization of accumulated power - and weapons-grade plutonium, and to dispose safely of radwaste, while developing fast neutron reactors and a closed fuel cycle.

According to the principles declared and on the basis of a detailed analysis of many factors of the nuclear power production the scale of nuclear power development for the next 10-15 years is determined by the **Power Strategy of Russia.**

The necessary nuclear level in 2010 would be 125 billion kWh (22 GW installed capacity)- i.e. 11% of the country's total electricity output. The maximum level of electricity production at NPPs in 2010 would be 160 billion kWh (28 GW installed capacity), i.e. up to 13 % of Russian's electricity production.

In the current period of economic transition in Russia there are many uncertainties which essentially complicate long-term forecasting of the expansion of the nuclear capacity. Thus, estimates of the possible variants differ to a great extent. On the other hand, the principal difference between the **Power Strategy of Russia** and the Power Programs of the former USSR should be emphasized. The **Power Strategy of Russia** is based on the new geopolitical situation, transition towards market-oriented, environmentally sound economies and also from the new function of the federal, regional and local authorities fixed in the Russian Constitution. The main task of the Strategy is not to determine the exact parameters of the future Russian fuel and power complex but to create the environment and conditions which could facilitate its development in the necessary direction.

2. SOME RUSSIAN REALITIES AFFECTING THE NUCLEAR POWER DEVELOPMENT UP TO 2010.

To determine the level of development of nuclear power and its structure, many factors are to be analyzed. Some of the major factors are as follows:

- Electricity demand expectations;
- Existence of natural uranium resources and their limits;
- Science and industry development level;
- Availability of up-to date nuclear power plant designs with safety features;

- The country's ecological safety and people health protection, public acceptance of the nuclear power;
- Economic indices for competition with conventional power.

Electricity demand . When analyzing the electricity demand in Russia the experts note the following paradox. On the one hand, the total power demand in the country has decreased while, on the other hand, there are regions of the Russian Federation with great electricity shortage. Even under existing conditions of economic stagnation the local governments of these regions are ready to support the construction of power plants.

The future electricity demand assessments for Russia were made for different options of the country's economic development [1], including the most optimistic and pessimistic forecast. Despite the fact that the highest priority **of the Power Strategy** is power saving, all the scenarios under consideration have shown an increase in the electricity consumption towards the year 2010 from 25% up to 40% above the existing level. If we also take into account the capacities of the power branch to be decommissioned by 2010, we may expect a rather bulky market of electricity demand .

Fuel . While a major problem of traditional fossil-fueled power plants is fuel supply which requires large capital investments, the nuclear power program up to 2010 could be run on already available cheap uranium stored. Thus, nuclear power is the only branch in the fuel and power complex structure which does not require mining in the immediate future. Even if we take into account for Russia's export of uranium products, there will be enough left to fuel any version of nuclear power development up to the year 2010 [1, 2].

Nuclear science, technology and component - manufacture. It is rather natural that the Chernobyl accident, the former USSR disintegration and economic stagnation negatively affected the nuclear science and technology potential in Russia. This potential was mainly concentrated at the territory of Russia and objectively has appeared surplus for the new and much lower rates of nuclear power development. All these circumstances have resulted in the very difficult and painful processes of reduction and restructurization of the nuclear domain. Nevertheless, existing industrial and construction enterprises and infrastructure still have a great potential. For the version of a maximum nuclear power development from 1997 to 2010 , the " Izora Plant" will make on average 1.38 sets of equipment per year with an average power of 782 MW/year; " Atommach" will make 1.62 sets per year with an average power of 1187 MW/year; "Leningrad Metals Plant" will run at 75-100% of its manufacturing capacity [2].

Therefore, the existing nuclear scientific, technical and industrial basis of Russia renders the program of nuclear power development up to year 2010 quite realistic, as well as carrying out of the perspective R&D and work on new designs.

New designs with improved safety features. New designs considered as priority for the construction of leading NPPs are [2]: WWER-640 (NP-500 design) with a capacity of 1800 MWth at the Sosnovyi Bor (Leningrad region) site; WWER-1000 (NP-1000, NP-1100 project) with a capacity of 3000-3300 MWth at the Novovoronezh NPP. Decrease of reactor capacity and of core power density in these designs gives additional opportunities for considerable rise of safety, while providing competitiveness. The fast neutron nuclear power installations BN-800 (2100 MWth) to be constructed at the two Ural sites are not only designed to generate electricity and district heating but to burn up weapons-grade plutonium and actinides. To supply energy to industry in remote areas, several designs of nuclear power installations and low-power NPPs (2.5 to 150 MWth) are available.

Safety, people's health, environmental protection and public acceptance. Does the nuclear fuel cycle really have ecological advantages when compared with the fissile fuel cycle or not? This question is very important for the further development of nuclear power.

Under normal operation radioactive contamination of the environment beyond the NPP site boundaries is within the natural background level. Stable NPP operation is one of the environmental improvement factors. The analysis of atmospheric releases of Russia's electricity power has shown that while producing about 12% of the total electricity in the country NPPs and nuclear fuel cycle plants are emitting only about 3% of sulfur dioxide, 0.5% of carbon monoxide and 0.9% of nitrogen oxides. The public exposure near NPPs is determined by natural sources of radiation. The average annual dose of personnel at WWER and BN-type reactors is about ten times less than the maximum dose allowed.

But all these (and many other) ecological advantages of nuclear power can of course only be appreciated when the necessary safety level is ensured at the same time. Most Russian specialists and officials are aware that the nuclear industry is not prepared to face another accident approaching anywhere near the scale of Chernobyl. So there is a continuous effort to improve safety performance at all operating NPPs in Russia and most of the financial sources guaranteed for nuclear power of late (including return on capitalization) were invested in their reconstruction and technical improvements.

Transition to market relations in the country presumes that a certain economic status is given to nuclear power and it implies a new and much more important role of the public opinion in the realization of the nuclear power program. The cooperation with the public and local authorities in the regions of NPP sites are gradually beginning to take shape. This process of adjusting to new realities is being much complicated by the irreconcilable and inconstructive opposition to nuclear power. The ecological aspects of nuclear power development are the main targets for criticism. Lately, to the traditional objects of attacks which have been nuclear safety and radioactive waste disposition a new one has been added, i.e. the ecological aspects of ex-weapons plutonium utilization options.

In any case anti-nuclear opposition in itself is a new reality of nuclear power development in Russia and it should be taken into account in the same way as other factors for its development in the near future.

Economics. Most of the factors which have been considered above reflect the existing possibilities of the Russian nuclear sector and gives an opportunity to make an optimistic power projection up to 2015 . It is supposed that units at Rostov, Kalinin and Kursk NPPs will be put into operation in 1999-2000. At the same time, the first generation NPPs of about 9 GW installed capacity are being decommissioned before 2010. As regards the units of the second generation, MINATOM's policy set the task to consider the possibility for 5-10 years of operation life extension beyond the design operation life.

Unfortunately, the economic situation in the country requires at the same time a more careful outlook. The immense capital investment costs, long licensing and construction periods and return on capitalization are not in favor of nuclear power in the existing investment climate in the country. In the authors' opinion, the investment problems are among the weakest links in the Russian nuclear power program up to 2010 and it requires the consideration of a pessimistic option which is close to a simple compensation of removed capacity (Fig.1).

But, of course, an unfavorable investment climate may not only slow down nuclear power development. The financial obstacles mentioned above are typical for the fuel-power branch as a whole. Thus, key questions to be answered in the economic area are: has nuclear power sufficient competitive ability in realistic scenarios of power development in Russia and what regions are the most suitable sites?

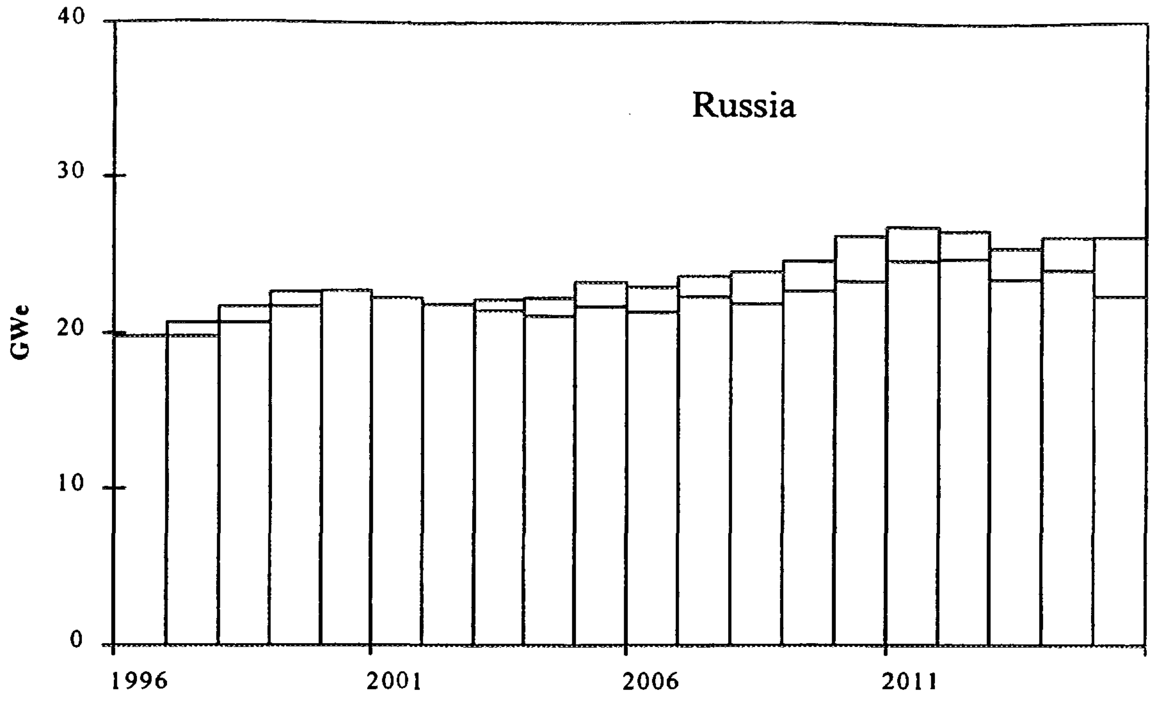

FIG. 1. Russia Nuclear Power Outlook to 2015.

3. ASSESSMENT OF NUCLEAR POWER COMPETITIVENESS IN SOME REGIONS OF RUSSIA WITH IAEA'S PLANNING TOOLS

Nowadays, economic methods and tools used in Russia are being adapted to the realities of market relations forming in the country.

In the process of analysing the competitive ability of NPPs on the Russian power market it is highly desirable to utilize a sound methodology allowing to properly account for the related technical, economic and environmental issues and thus to provide reliable information to decision-makers. In this respect, the use of energy planning tools supported and distributed by the IAEA that are widely used for energy planning purposes in many countries can become a valuable input to the process of the preparation of the strategy and, as a complement to other national studies, can provide important information for making decisions on further development of nuclear power in Russia.

Several IAEA planning tools were applied in Russia [3]. They included some modules of the ENPEP [4] package, the Wien Automatic Planning Package WASP [5] being one of them, and the DECADES database system. The MACRO and DEMAND modules of ENPEP were used for making up electricity demand projections in Russia; the WASP model was used for assessing the long-term role of nuclear power on the basis of development of an optimal capacity expansion plan for one of Russia's regions; finally the DECADES package was used for the development of a database of technical, economic and environmental parameters of various electricity generation chains and for a chain-by-chain comparison of the nuclear electricity generation chains with their competitors.

As the object of the WASP application [3], a power pool serving a large territory in the centre of Russia was selected. This power pool, which is called the Central Power Pool (CPP), is the largest component of the integrated power system of Russia. The installed capacity of the CPP is ~ 50 GW or about 1/4 of the total electricity generation capacity in Russia. There are more than 80 power plants in the system. They include plants using fossil fuels, nuclear power plants and hydraulic plants.

The scenario of fuel price escalation was taken from [6] and is based on the assumption that the escalation of fuel prices to the world market level is part of the consequences of the transition to the market economy. Lower rates for nuclear fuel were also assumed: gas/fuel oil - ~7.5% year; coal - ~7% year; nuclear fuels - ~4.3% year. This is one of the potential sources of the economic competitiveness of nuclear power in the future.

The structure of the optimal capacity expansion plan developed with WASP-III Plus is shown in Fig. 2. One can see the structure of the optimal solution and note the following characteristic features of the optimal capacity expansion plan:

- Until 2004 there is no need for new electricity generation capacities due to the drop in demand in the 90s.

- The optimal solution includes four types of electricity generation: combined-cycle units, conventional gas-fired units, nuclear units and gas-turbines.

- At the beginning of the planning period (1994), gas-fired technologies are economically the best due to rather low gas prices at that time. However, as gas and coal become more and more expensive reflecting accelerated escalation of fossil fuel prices, nuclear power becomes competitive and nuclear units start to enter the optimal solution. As a result, it is the nuclear unit that enters the system first when new capacities are required (2004). At the end of the considered period (2015) there are two nuclear units in the system. The remaining part of the new capacities are mostly gas-fired units with combined-cycle units being predominant.

- There are no inputs of new coal-fired units in the optimal solution, the reason being too high capital costs.

On the whole the results obtained by using IAEA's planning tools are very near to those obtained with the use of the new domestic methods and tools. The wide analysis of the competitive ability of designed NPPs on the Russian power market, if compared with fossile fuels, made it possible to determine the regions where the competitive ability of nuclear power is highest. Such regions have been determined together with the factors of admissible exceedings of the capital investments of NPPs over fossil fuel power plants.

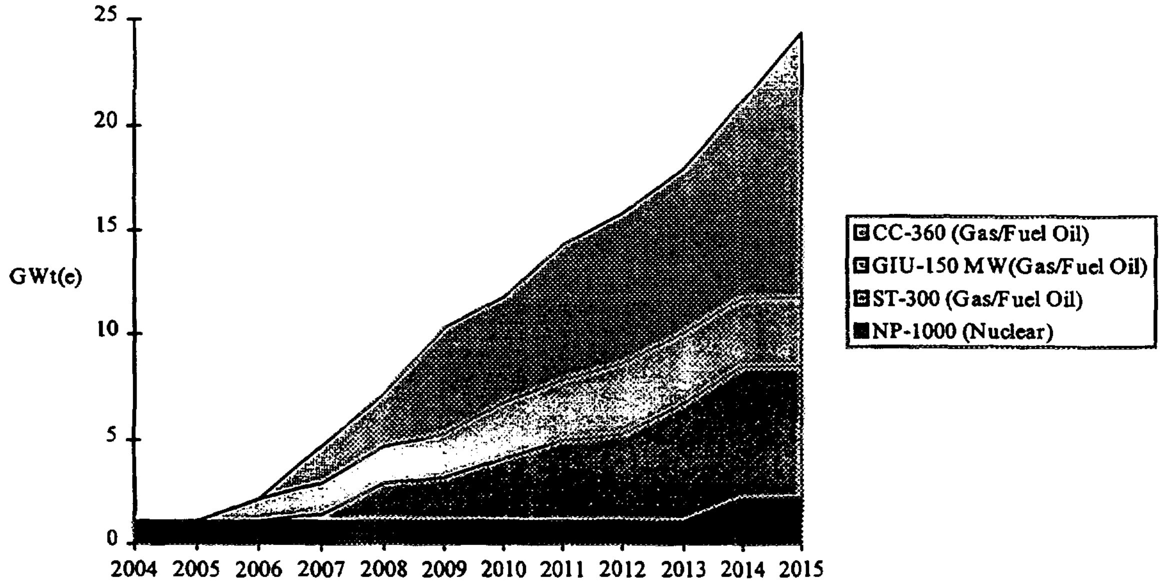

FIG. 2 Composition of the Variable System (Inputs of New Capacities).

It is worth mentioning that some authors of economic studies come to the conclusion that nuclear power is competitive almost all over Russia including Siberia [7].

4. METHODOLOGICAL APPROACHES FOR EXTENDING THE HORIZON OF NUCLEAR PROJECTIONS BEYOND 2010

When speaking of the nuclear projections beyond 2010, economic assessments alone seem to be insufficient and ecological criteria much more reliable today. This is especially true if we take into account the still rather weak but very important tendencies in the world towards approaching economic and ecological criteria. We believe that, at the end of the road, ecologically safer systems would appear economically preferable.

The authors chose the following three issues among the many important ones that are related to this problem:

- Conserving natural uranium resources and thereby decreasing the environmental impact at the initial stages of the nuclear fuel cycle;
- Minimizing the plutonium stockpile;
- Reducing radiotoxical waste to as low a level as modern methods can achieve (ALARA principle).

The country's nuclear power program up to 2010 could be run on already available cheap uranium stored but considering a more long-term perspective some experts point out that a new situation has arisen from the disintegration of the Soviet Union. Namely, total explored reserves of natural uranium are being estimated to amount to 450 thousand tons, reliably assured resources (RAR category of the IAEA classification) come to about 300 thousand tons [8] . Such reserves are not sufficient for 80 GWe nuclear power generation in thermal reactors after the year 2030, and for 50 GWe after the year 2040 (Fig. 3). Plutonium utilization is the most reliable way for Russia to provide itself with nuclear resources in the future. The alternative is buying uranium on the world market at world prices.

It is well known that the Russian strategy is based on the concept of fuel reprocessing and recycling reusable materials: uranium, plutonium and minor actinides. An available park of reactors and of new designs to be constructed in the nearest future make it possible to scrutinize the different structures of future reactor systems (Fig.4).

The open cycle in variants '1 and '2 is being realized now in Russia. The next variant ('3) is the monorecycling cycle which is realized in Western Europe.

A specific feature of Russian nuclear power is the successful development of the fast reactor technology. It gives an opportunity to consider in a not too remote future the systems containing this type of reactors. Introducing fast reactors in the nuclear power structure with the aim to burn plutonium and minor actinides (neptunium, americium, curium) from the WWERs is the essence of variant '4. The recovered uranium is recycled and reenriched and then returned to thermal reactors. Plutonium is recycled to provide at first the fissile material in WWERs and then to be used in BN-800 with the breeding ratio 0.8. All extracted minor actinides are utilized in fast reactors.

It is interesting to scrutinize also the two-stage system including WWER and BN reactors (variant ' 5).

A monosystem of fast reactors with a breeding ratio equal to one is an asymptotic case of such a consideration (variant ' 6).

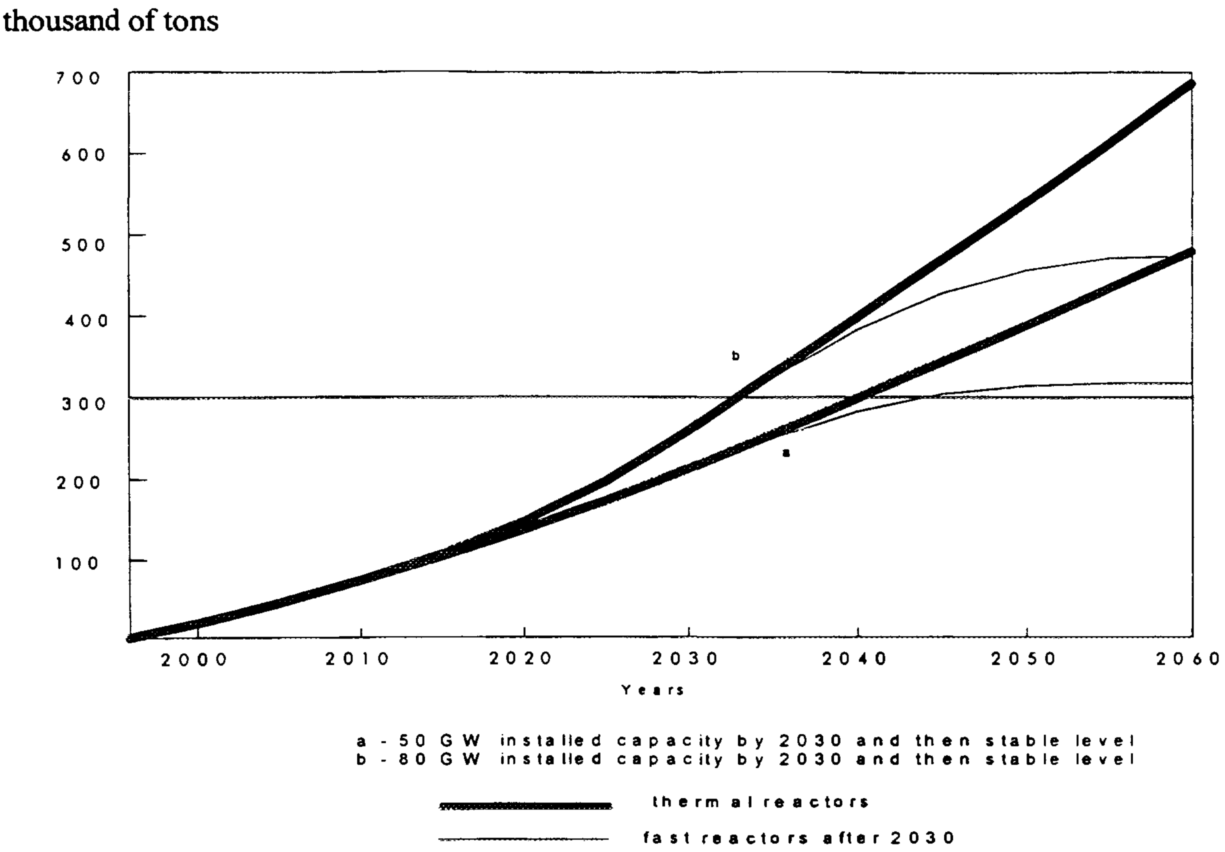

FIG. 3 Natural Uranium Demands for Russian Nuclear Power.

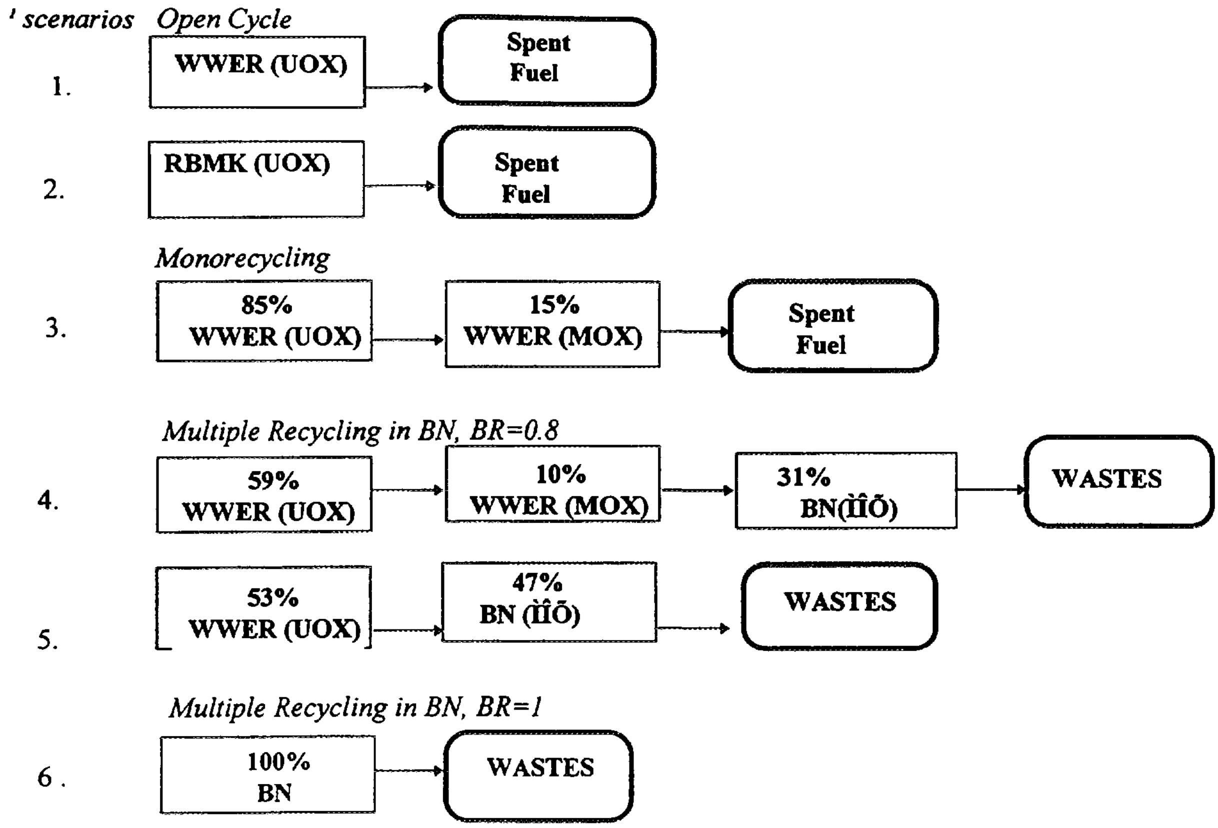

FIG. 4 Scenario of Nuclear Power Development Based on WWER-1000, BN-800 Reactors.

It is necessary to note that due to its splendid physical properties the fast reactor may ensure breeding of the nuclear fuel as well as burning of the excess fissile materials. Moreover, switching over from one function to another is possible at the reactor unit by changing only the core.

The results of our study are represented in Figures 5-8.

One can see that monorecycling (variant ' 3) provides an opportunity to ensure nuclear power generation up to year 2030 with the use of reliably assured uranium resources alone and then to maintain during 30 years nuclear power generation with an installed capacity of about 20% more than in the strategy based on the open cycle (Fig. 5). The specific need for natural uranium resources is reduced by 1.4 times when compared with variants ' 1 and ' 2 (Fig. 6).

This option saves about 100 thousand tons of natural uranium for 50 GWe nuclear power generation operating 30-35 years, or approximately half of the country's uranium resources with the price remaining below $ 80 per kg. At the same time, as shown in Figure 5, once-through recycling in thermal reactors will only postpone the problem of uranium deficit but not resolve it even for a century.

One can mark the significant decrease of the specific radwaste mass in variant ' 3: to a factor of 3 compared with open cycle option ' 1 and to a factor of 6 compared with option ' 2 (Fig. 7). But the reduction of the specific mass of plutonium and minor actinides is not so essential. Moreover, the specific mass of minor actinides in spent fuel in variant ' 3 is even increased compared with variants ' 1 and ' 2 . In fact, PWRs are not good instruments for the transmutation of minor actinides, the capture cross section for them being much larger than the one for fission.

The introduction of BN-800 type reactors into the system - the installations with a hard spectrum of neutrons (variants ' 5 and ' 6) lead to a fundamentally new situation (Fig. 7- 8) . Uranium, plutonium and minor actinides will be "closed" in the cycle and their release into the environment will be insignificant and only inevitable losses from technological operations in chemical processing. Thus, nuclear wastes of the systems including fast reactors will consist mainly of fission products, which is 25-50 times less than the amount of radioactive wastes for the once-through fuel cycle.

Simultaneously, multirecycling allows for a further essential reduction of the need of resources to a factor of 2.5-4, when compared with the open cycle variants (Fig. 6). The "pure" system of fast reactors is the most effective from the point of view of uranium resource conservation, depleted uranium only is being consumed in the case. It is also very good from the standpoint of radwaste minimization, since the efficiency of heat conversion into electricity in fast reactors is more than in thermal ones. So, at the same level of electricity production, fast reactors need less amount of fuel to be fissioned.

In spite of the very good properties of the only fast reactors system the authors do not incline to consider any monosystem to be an asymptotically optimal structure.

Enriching of nuclear power with fast reactors seems to be rather a kind of beneficial tendency than a final aim. In the near future the wide introduction of fast reactors for nuclear power generation will be delayed by their high cost; in a more distant future, one may expect the creation of nuclear installations with qualitatively new properties in respect of nuclear safety and burning of long-lived fission products. System analysis of nuclear power development beyond 2010-2015 is a problem of exceptional difficulty and this study is, of course, only a tiny contribution to it. Nevertheless, the criteria of natural resources conservation, minimization of accumulated hazardous products and waste will be the reliable landmarks in any consideration since they make it possible to construct a nuclear power system in accordance with the natural ecosystems which are known to be an ideal model of interaction with the environment.

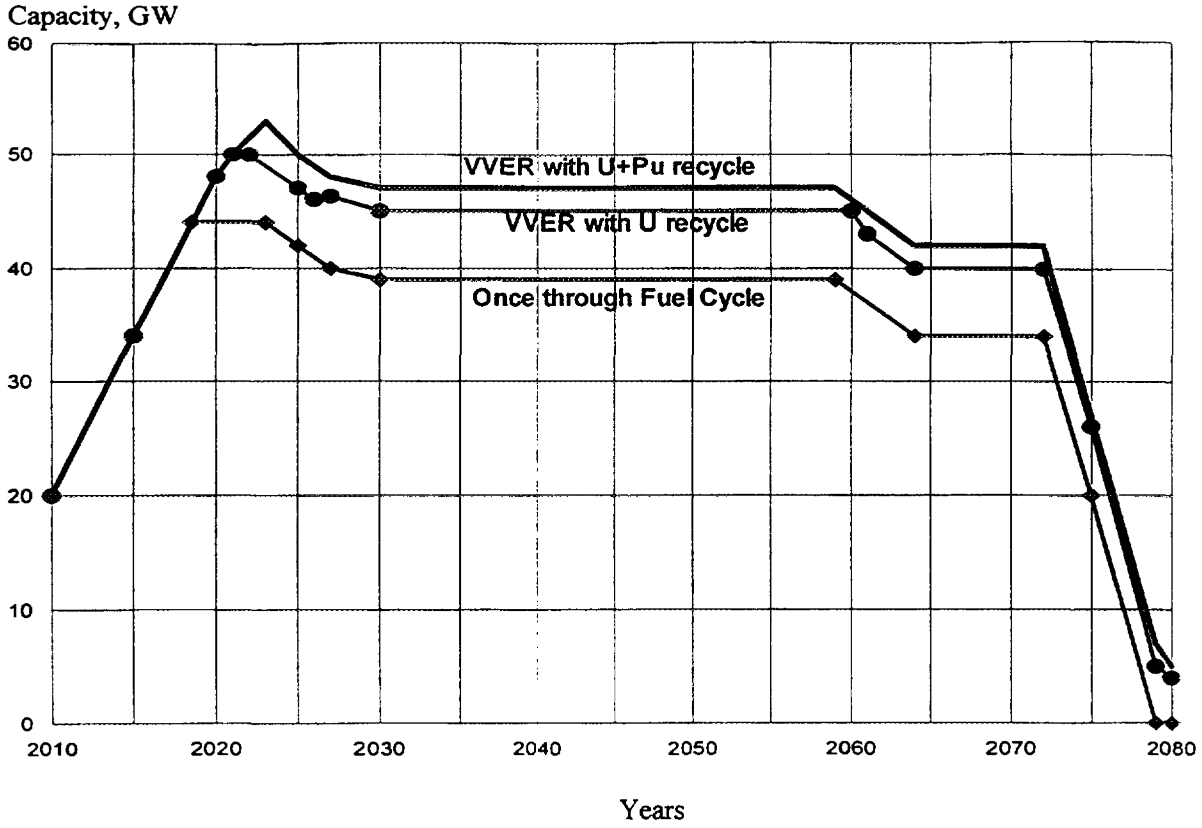

FIG. 5 The dynamics of NPP' capacity in once through and closed WWER nuclear fuel cycle

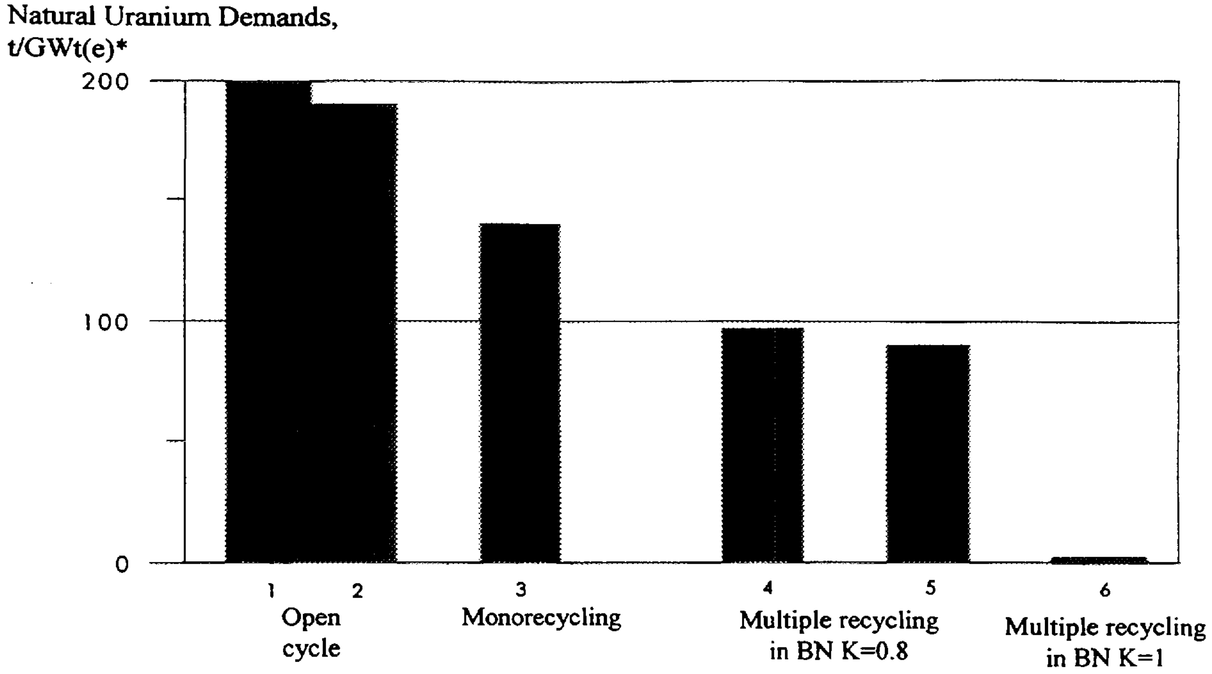

FIG .6 Specific Natural Uranium Demands for Different Scenarios of Nuclear Power Development

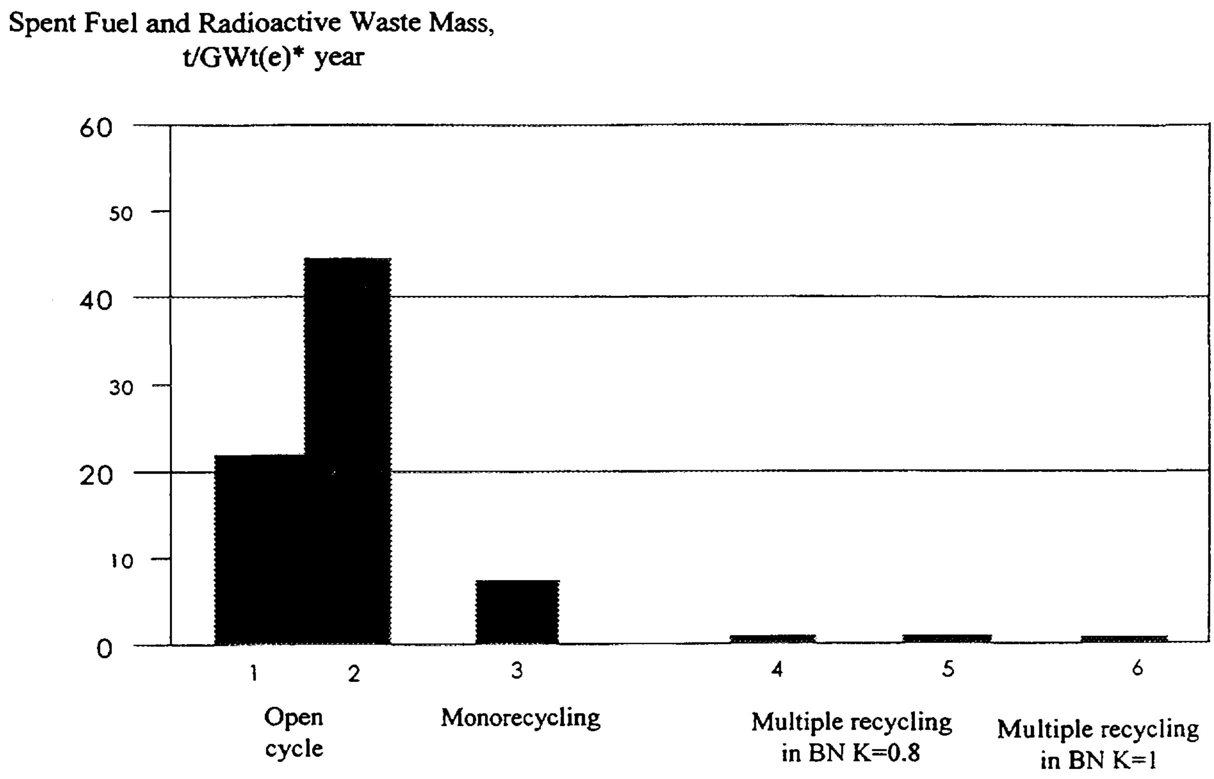

FIG . 7 Specific Spent Fuel and Radioactive Waste Masses for Different Scenario of Nuclear Power Development.

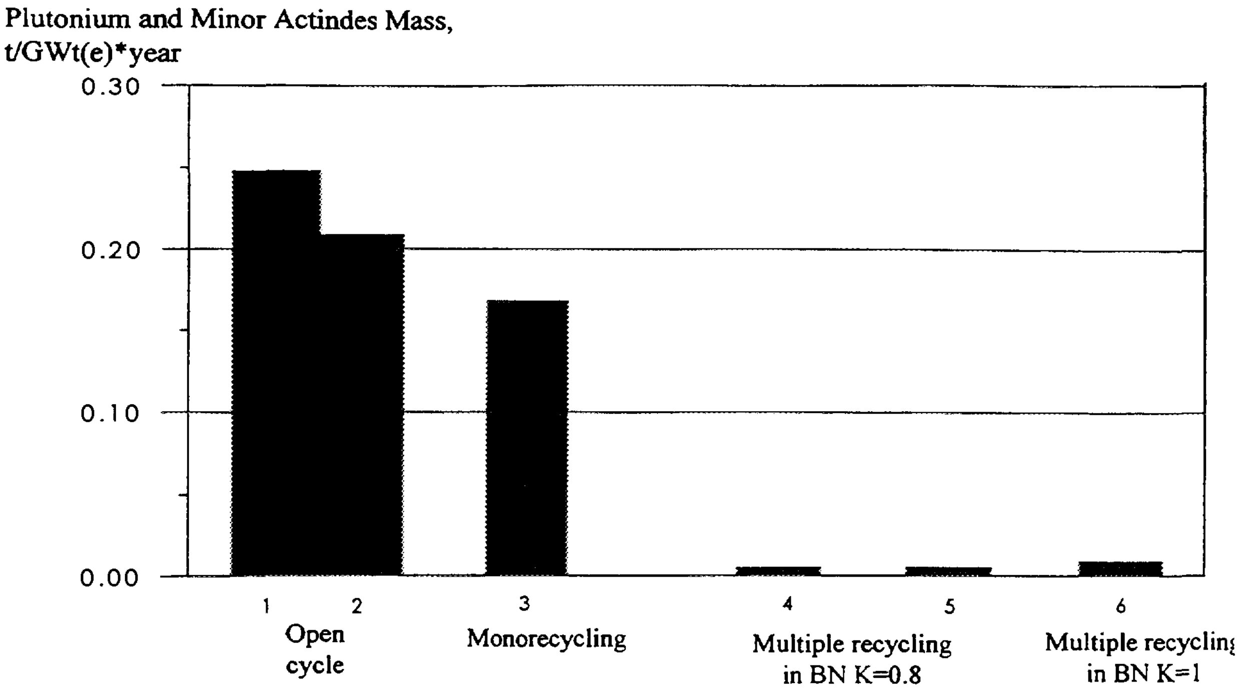

FIG. 8 Specific Plutonium and Minor Actinides Mass in Spent Fuel for Different Scenario of Nuclear Power Development.

5. CONCLUSIONS

(1) In accordance with the Russian power strategy a moratorium on nuclear power development is inadmissible and a part of the electricity production in the country will be covered by nuclear power plants. Increasing of safety is the major priority of the nuclear policy.

(2) The market-oriented planning tools confirms the competitive ability of nuclear power in many regions of Russia, if compared with fossil fuels.

(3) From the authors standpoint the investment climate in the country is the most important and the most uncertain factor to influence the nuclear power development up to the year 2010.

(4) The plutonium balanced system of thermal and fast reactors has very good ecological properties from the standpoint of the conservation of natural uranium resources and of the waste minimization of uranium, plutonium and minor actinides.

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