SOME CONDITIONS AND PROSPECTS OF TRANSITION TO CLOSED FUEL CYCLE IN RUSSIA

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ABSTRACT

Nuclear policy of Russia is based on the necessity of closure of nuclear fuel cycle. But at the same time schedule of such a going is not defined. In this study some conditions and possible time-frames of going the nuclear fuel cycle of Russia to closure are discussed. Naturally, the main condition is revival of Russian economy wherein nuclear power will turn to be necessary in a number of Russian regions. But the question is whether closure of nuclear cycle strategy will be implemented in the near future or nuclear power will develop based on open fuel cycle over a long period of time? At present economic circumstances in Russia has formed in such a way that economics of current projects is not favourable to going to closure of cycle due to high capital investment cost and low fuel component of costs, due to low cost of natural uranium. Ecological analysis performed within the framework of external cost model also does not suggest that closed cycle has essential advantages at present, but also in sight. The authors have considered a model including not only external costs but also total resources expenditures with long-term power development. In the framework of such a method it can be demonstrated that closed fuel cycle has some important advantages taking into account not only tasks of immediate future, but power development strategy for the period of 30-50 years. Under conditions of nuclear capacities increase (to 30-50 GW) limitation of cheap uranium resources available in Russia will assume a new significance. Approach of prices at the backend stages of nuclear fuel cycle to West Europe level also will favour to going to a closed fuel cycle. More severe ecological requirements answering to a sustainable development concept also will make a contribution. Closure of fuel cycle can be significantly accelerated in the case of implementation of weapon plutonium utilization program. The factors mentioned above facilitate evenly to going to a closed nuclear fuel cycle in Russia.

INTRODUCTION

As is well known, in the open nuclear fuel cycle (NFC) the uranium fuel is used once, mainly in thermal reactors (at present in Russia in the open cycle uranium fuel is also used in the BN-600 fast reactor). At high pace of development of nuclear power, shortage and (or) high cost of uranium fuel, a closure NFC on plutonium becomes justified (return of plutonium after chemical reprocessing in a cycle as nuclear fuel), and the problem of fuel supply is principally solved by means of fast breeder reactors. The actual situation of the last 10-15 years by virtue of a series of the reasons, in the first place economic, has not confirmed as a whole the forecasts made in 60-70-s concerning high pace of development of nuclear power. Therefore at present it is possible to speak about essential correction, down to radical revision, of nuclear strategy in many countries of the world, including Russia.

The long-term nuclear strategy of Russia is still based on the necessity of closure of a nuclear fuel cycle. As is well known, Russia to a greater or lesser extent has a practical experience concerning implementation all stages of closed NFC. But at the same time the rate of transition to a large-scale plutonium use has obviously slowed down recently. The main reason of this deceleration was the economic recession, which has entailed sharp decrease in demand for the electric power, as well as grave consequences of the Chernobyl accident which had undermined substantially the confidence to safety of nuclear power. Naturally, that only under condition of revival of Russian economy and long NPP operation at an acceptable level of safety it is possible to expect that nuclear power, including the fast reactors, will turn out to be called for again. But at such development of events in the absence of additional stimuli to use of plutonium terms of implementation of strategy of the closed cycle can be postponed on 20-30 years.

This report presents consideration of some aspects of a real situation in nuclear sector of Russia, which objectively promote acceleration of transition to plutonium burning in nuclear reactors. It is shown that the implementation of plutonium burning strategy in the near future becomes justified only at a very wide sight on a problem, which includes not only national interests of Russia, but also fundamental factors of international safety.

ECONOMIC ASPECTS

At first let's make some remarks concerning the technical and economic aspects of use of plutonium-based fuel, restricting consideration by NPP's level, that is taking into account commercial interests and technical opportunities of the NPP's owners as the subjects of economic activity.

In 1999 the nuclear power of Russia had total installed capacity 21,4 GW, from them: 45% of VVER reactors, 55% of RBMK reactors and others. As the nearest outlook of development of reactor park the design of the advanced VVER reactors (VVER-640, VVER-1000) of increased safety as well as design of a the BN-800 fast reactor, having now the largest degree of readiness to introduction, are considered.

The Table 1 represents quantities of specific capital cost and electricity generation cost for new power units with VVER reactors on uranium fuel in comparison with power units of the same type, but with MOX-fuel, and in comparison with power unit with BN-800 reactor.

These data are received on the basis of the analysis of the published materials, in particular (1-5), and own estimations of the authors. High uncertainty of the estimations is related to the fact that they are not assigned to the designs of particular power units, placed on particular sites. Besides, the problem of plutonium recycle in VVER-reactors has arisen rather recently and just tentative estimations of costs have been received (basically within the framework of international cooperation). Apparently, both specific capital investments and electricity generation cost at NPP with VVER-reactors operating on MOX-fuel will be higher in comparison with NPP with standard uranium VVER-reactors. This is because MOX-fuel, in comparison with standard uranium fuel, has a number of properties, which can require modification of some modules and equipment on NPP:

- Higher thermal flux from fresh and spent MOX-fuel;
- Higher level of radioactivity of MOX-fuel;
- Toxicity and high migratory ability (volatility) of plutonium.

On the basis of an estimate of these and a number of other factors, the authors received quantities of coefficients describing the ratio of specific capital investments and electricity generation cost for VVER on MOX and UOX fuel. Though these estimations have high uncertainty and they should be considered as just preliminary, nevertheless, they allow to reveal some important tendencies and to make on their basis rather definite conclusions.

The Table 1 shows, that the fast reactor with MOX-fuel has higher cost, than a light water reactor on uranium fuel, both on specific capital investments (up to 1,5 times), and on electricity generation cost (up to 2 times). The relevant indicators for VVER on MOX-fuel are slightly better, than for power unit with a BN-reactor, but worse than indicators VVER on UOX-fuel. The prospect of competitiveness of the fuel cycle with MOX-fuel is primarily connected with a fuel component, however, today it is not lower, than fuel component of the open cycle.

The data from work [6] testify that MOX-fuel cost will be approximately 6-20% higher than that for uranium fuel, depending on particular values of uranium and MOX-fuel fabrication cost, as well as on cost of separation. Hence, based on the achieved technical and economic characteristics of reactors on MOX-fuel, one may conclude, that at present conditions for the large-scale commercial plutonium utilization are absent in Russia.

When analyzing economic advantages and disadvantages of open and closed cycles at NPP level, unequal conditions of their comparison, of course, should be kept in mind, first of all, different degrees of technical development. By now the studies have been executed showing that at industrial construction the fast reactors will come nearer to light water on the economic characteristics. As the share of capital component in electricity generation cost on NPP is determining (60-80%), the main attention is given to measures on its decrease. In report [7] the comparison of indicators of the European fast reactor (EFR) and advanced light water reactor of PWR type is performed. It is shown, that providing capital component of EFR exceeds this component for PWR by 26% and uranium price is more than 100 $/kg, electricity generation costs will be approximately identical. At such a price of uranium, the high specific capital costs of fast reactor are compensated for by high fuel cost of light water reactors. As uranium market price is much lower now, the further decrease in a capital component for fast reactors is necessary.

TABLE 1. Capital investment and electricity generation cost for nuclear units

Characteristic	VVER (UOX)	VVER (MOX) in relation to VVER (UOX)	BN (MOX) in relation to VVER (UOX)
Net overnight costs	1000-1500 $ /kW(e)	1,05-1,1	1,1-1,5
Electricity generation cost, including:	1,4-1,6 cent/kWh	1,1-1,3	1,3-2,0
Fuel costs	0,4-0,6 cent/kWh	?-1	?-1,1

The search for ways of decreasing capital component of electricity generation cost is the subject of special attention in investigations on improvement of the technical and economic characteristics of fast reactors, pursued by scientific and design organizations of Russia. It is suggested in work [3], for example, that under conditions of toughening the requirements on the safety of nuclear units with thermal reactors and at industrial construction of BN-reactors their economics comes nearer to that of VVER-reactors. The comprehensive substantiation of such a conclusion at the technical design level could be a deciding factor to promote realization of the existing construction plans for the first power unit of BN-800 reactor in 2010-2012 years [8]. More conservative estimates, partly reflected in the Table 1, indicate that in the coming 20-30 years it will be impossible to approach economics of fast reactors to thermal one. As follows from the Table 1, it is more likely to expect such an approach for a thermal reactor with MOX-fuel, however in this case plutonium recycling in thermal reactors at the initial phase will be noncompetitive in comparison with reactors with standard uranium fuel.

Consequently, with low natural uranium price and absence of the forecasts of its growth in the near future the transition to the closed fuel cycle with repeated plutonium recycling in fast reactors or with one-double plutonium recycling in light-water reactors is not economically justified in the context of NPP competitiveness. The situation appears different if one would broaden the scope of economic system under consideration and take a look on the problem from the position of national or even international interests. The methodology of the above mentioned approach has been developed within the framework of the ISTC Project №369 [9], performed with financial support of European Union. In this work the authors proceed from the same fundamental concept, but in substantially simplified form.

It is well known [10], that according to the Treaty of the Non-Proliferation of Nuclear Weapons (NPT) Russia and other nuclear States undertook “to pursue negotiations in good faith... on general and complete disarmament under strict and effective international control”. The USA and Russia have declared presence of excess weapons plutonium and gradually initiate with its destruction. In the last few years the process gained in strength, however, as it was predicted by the outstanding scientists and politics at the earliest stage of making of a nuclear bomb, not only creation, but also disposal of the nuclear weapon has turned out to be connected with the great expenses. One of the fundamental problems arising in this connection is whether this expensive way of reactor utilization of weapons plutonium withdrawn from defense sphere could be economically justified in whatever sense or not?

On 41-st IAEA session (October, 1997, Vienna) it was announced about the decision of Russian Federation concerning gradual withdrawal of up to 50 tons of weapons plutonium from the nuclear military programs. Cost of plutonium storage in the USA and Western Europe considering modern measures ensuring protection against proliferation and ecological safety, makes up to 2 American dollars per gram annually [11, OECD/NEA]. Of course, in Russia plutonium storage, including weapons, is much cheaper. However, as the country joins in the world economic system, the situation should change. Approach of domestic prices on natural resources and manpower to the world ones, transition to contract-based military service, strengthening of international cooperation in the field of safeguards implementation and other integration processes will inevitably entail approaching to the world standards in the field of safe management and storage of fissile nuclear materials. At present Russia already receives international assistance in building stockpiles for long-term storing of nuclear warheads, taking into account all necessary requirements of nuclear non-proliferation and corresponding expenses.

If during the 21’st century activity in this field will be restricted by national efforts and assistance of World Community only in building reliable stockpiles for plutonium, and large-scale utilization of its energy potential will not come into operation, then integral expenditures for plutonium stockpiling within the specified boundary conditions would be about 10 billion US dollars (Figure 1).

Preliminary results of calculations performed on the basis of initial data presented in Table 1 show, that even for the worst economical parameters of fast reactors, integral expenses of the same scale as for plutonium storing, but used for reactor utilization of plutonium, will allow to solve the problem of 50 tons plutonium stockpile by means of reactor system consisting of three fast reactors approximately by 2023 (Figure 1). This scenario implies utilization of plutonium until 2010-2015 in presently operating fast reactor BN-600, and later in two BN-800 reactors to be commissioned with the interval of 2 years.

Scenario of plutonium stockpile utilization by means of four VVER-640 reactors to be commissioned successively with the interval of 3 years starting from 2010 requires even less integral expenses, though in this case the utilization mission will last approximately until 2038.

In that way, if one considers incineration of weapons plutonium in reactors as one of the ways of nuclear disarmament problem solution, it should be recognized that additional expenses for MOX fuel cycle implementation are justified, as in the end it will lead to elimination of weapons plutonium stockpile and continuous expenses for its support and maintenance.

ECOLOGICAL ASPECTS

From the position of the modern methodological approaches of ecological safety substantiation, the utilization strategy of the released plutonium also can be considered as justified one. At first let’s compare the

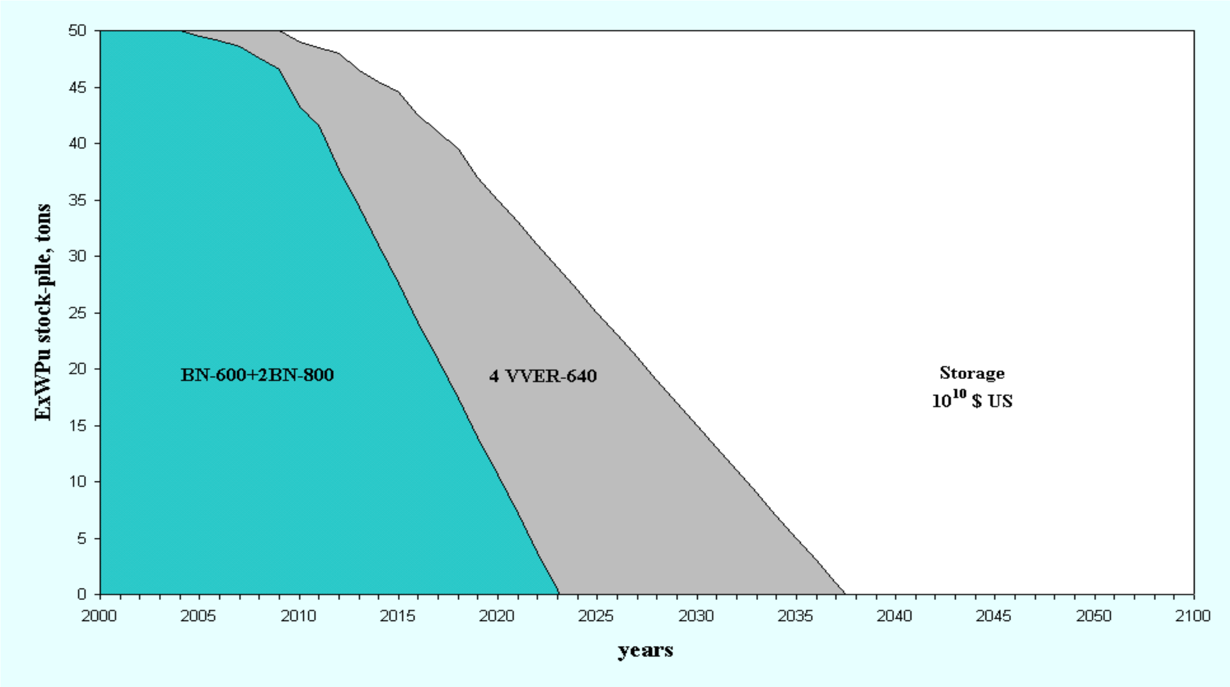

FIGURE 1. Economics of options of the ExWeapon Pu stock-pile reduction versus a century proliferation safe storage

situation from the point of view of open and closed NFC impact on the population and personnel health.

Radiation factor is considered as the main component of health impact from NFC facilities. The multiple pathway analysis of exposure was used as the general methodology of assessing radiation impact doses. This method includes the description of radionuclide transfer pathways from the sources of radioactivity to a human beings. The data on radionuclide releases, observational data and calculation estimations of radionuclide content in objects of the environment are used as an initial information.

The methodology requires comprehensive and labour-consuming algorithms of calculation, and its development is going smoothly. The calculation results are being compared with the published results of the various authors and with the information from the databases of international organizations, in particular, International Atomic Energy Agency (IAEA). In Russia in various organizations, such as Biophysics Institute, ecological organization "Typhoon", Kurchatov Institute, IPPE and others, data on impacts from the specific NFC installations of Russia on the health and biota are also being accumulated, the part of them is presented in the Table 2.

When performing calculations, atmospheric releases and liquid discharges were taken into account. The following pathways of radiation impact on human beings were evaluated: external dose from the radioactive cloud and contaminated soil surface; inhalation dose from the contaminated air; and internal dose from the consumption of contaminated agricultural and natural products.

Dose assessments have been made for each radiologically significant radionuclide by all possible pathways of exposure on the following time and space scales. Time scales: short-term (less than 1 year), intermediate-term (1-10^2 years) and long-term (10^2-10^5 years). Space scales: local (0-10^2 km), regional (10^2-10^3 km) and global (over 10^3 km). Dose assessments for liquid discharges were placed into the regional category, since it is difficult to separate local and regional effects for them. Special attention was given to assessments of doses from the radionuclides of global spreading (^{3}H, ^{14}C, ^{85}Kr and ^{129}I). As a rule, the estimations for long-term intervals and large scales of territories are characterized by the greater quantity of indeterminacy [12]. In the Table 2 the published data are marked out with bold-faced font, estimations of the authors – with ordinary font.

Generalized assessments of the public collective dose commitment at different stages of Russian nuclear fuel cycle (without reprocessing stage) were given by Kryshev and Ryazantsev in [12]. The data on collective doses of the personnel on NPP are taken from yearbooks published RosEnergoAtom [13]. The greatest uncertainty is contained in the assessments of collective doses at the stage of fuel reprocessing. The values of radioactive releases of the RT-1 reprocessing plant operating in Russia are given in and on their basis, generally speaking, it is possible to make estimations of collective doses on the population. However, results received at such approach are hardly suitable for comparison of characteristics of open and closed fuel cycles. Firstly, technical characteristics of the RT-1 plant, commissioned in 1977, do not reflect the progress, that has been achieved in the technology of radiochemical fuel reprocessing recently. Secondly, the plant partly works for defensive problems, that impedes the analysis of assessments, as some data necessary for calculations, for example amount of reprocessed fuel, are classified. Therefore, assessments presented in the Table 2, are made on the basis of the published materials on the French plants on cape La Hague [14].

As a whole, the data on collective doses in NFC of Russia conform well with assessments of widely known "External Study" [14], realized under aegis of the European Union. In particular, the values of the contribution of electricity generation stage on NPP to a collective dose received by the personnel and the population during a complete cycle, presented in the Table 2, are of the same level as those for operating French NPP "Tricastin" [14]. It is necessary to mention that besides rather high indices on labor and health protection achieved at Russian nuclear installations, lesser averaged population density in Russia is also affected the result.

The main conclusion which can be made on the basis of the data from the Table 2 is that the values of collective doses obtained for VVER-UOX and BN-MOX variants in the medium-term period are rather close. In fact, the realization of plutonium recycling allows to reduce a collective dose due to elimination of mining and milling stage, but at the same time adds a dose at the stage of reprocessing. It is most probable, that the pure effect of these variants lies within the limits of data uncertainty.

Realization of the "restricted" closed cycle, when nuclear fuel materials come from the storage of earlier separated plutonium, gives additional effect on decrease of radiation impact on health of present generation at the expense of the previous generation, whose labour and health were expended on creation of nuclear reserves.

The system of data gathering concerning influence on biota is not elaborated in such a degree, as system for estimation of health impact. The very important factors of impact of fuel cycles on ecological systems are not taken into account sufficiently within the framework of methodology of an estimation of collective doses risks. Moreover, this methodology does not take into account even the factors of consumption of natural resources in, such as resources of fuel, fresh water, land, etc. The amount of generated nuclear wastes is taken into account only through the health impact.

The results of the study carried out on natural indicators of impact show, that in principle, closure of a fuel cycle affects positively the savings in natural resources. As it follows from the data presented in Table 3, realization of the closed fuel cycle requires less natural resources, including ground and fresh water, as compared to open fuel cycle.

TABLE 2. Medium Term Collective Doses, man. Sv/TWh

	VVER (OTFC)		**BN (Multirecycling)**	
	Personnel	**Public**	**Personnel**	**Public**
Mining and milling	$1{,}4 \cdot 10^{-1}$	$1{,}4 \cdot 10^{-1}$		
Fuel fabrication	$2{,}.0 \cdot 10^{-2}$	$5{,}0 \cdot 10^{-3}$	$1{,}0 \cdot 10^{-2}$	$7{,}1 \cdot 10^{-3}$
Electricity generation	$1{,}6 \cdot 10^{-1}$	$4{,}3 \cdot 10^{-2}$	$1{,}4 \cdot 10^{-1}$	$1{,}8 \cdot 10^{-1}$
Reprocessing			$4{,}0 \cdot 10^{-3}$	$6{,}0 \cdot 10^{-2}$ *
Transportation	$1{,}1 \cdot 10^{-3}$	$1{,}4 \cdot 10^{-2}$	$1{,}1 \cdot 10^{-3}$	$1{,}4 \cdot 10^{-2}$
Total	$3{,}2 \cdot 10^{-1}$	$2{,}0 \cdot 10^{-1}$	$1{,}5 \cdot 10^{-1}$	$2{,}6 \cdot 10^{-1}$

large bold print – detailed code analysis and measured data
small print – preliminary estimations
* Annual current collective dose at MAYK site is about 35 man. Sv

TABLE 3. Use of ground and fresh water at various stages of a nuclear fuel cycle

The stages of a nuclear fuel cycle	**Use of ground, ($10^4 м^2$/TVh)**		**Use of fresh water, ($10^6 m^3$/TVh)**
	temporary alienation	**long-term or final alienation**	**Total**
Mining and milling	2-7	0,2	0,02-0,2
Conversion	0,015-0,02	0,0015	0,01
Enrichment	0,017-0,025		2,0-6,0
Fuel fabrication	0,002-0,005		0,003
Electricity generation	5-10	0,003	1,32
Reprocessing	0,02		0,002-0,01
Waste disposal		0,01	

CONCLUSION

The study performed has shown that the attitude to the problem of plutonium utilization in Russia depends on scale of economic system, in which it is considered. At the level of NPP competitiveness, MOX-fuel cycle will lose to open uranium fuel cycle until the essential rise in price of natural uranium or decrease in capital costs required for MOX-fuel technology realization. At the same time, at the level of state interests and interests of world community it is economically justified to initiate elimination (reactor burning) of weapon plutonium, since otherwise great expenses for its practically termless storage will be needed, taking into account expensive measures required for maintenance and support of non-proliferation mode.

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