Scientific and technical problems of CNFC in two-component NPE and their solution in “Proryv” project

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Abstract. Modern Nuclear Energetics (NE) based on Thermal Reactors (TR) with Uranium fuel in Open Nuclear Fuel Cycle (ONFC) has systemic problems that limit its further development: low utilization efficiency of extracted U, absence of ecologically suitable solution for long-lived high-level radioactive waste treatment and nonproliferation. Besides that one of the most serious barriers for modern NE development is the problem of competitiveness that is closely related to safety problem. Attempts to solve the safety problem by development of additional active means of safety protection led to the decrease of competitive ability of NE compared to organic power industry. Fast Reactors with inherent safety as the basis for the New Technological Platform (NTP) are to overcome the current development barriers. The near future transfer towards the two-component NE structure with Fast and Thermal Reactors and CNFC is the key direction of the nuclear energy development strategy. Reprocessing of spent fuel (SF) and recycling of accumulated Pu and unburned U in Fast Reactors fuels cycle allows to cut the need in natural U in 100 times and in 10 times the mass of heavy nuclei in long-lived high-level radioactive waste, which is one of the key means of ensuring ecological safety of NTP. This article presents the goals and means of achieving technological and ecological safety, political neutrality, resource stability and competitive ability of the New Technological Platform. Introduction

1. Introduction
In the 70s of the past century, the world expert community had, by all means, optimistic forecast of the nuclear power industry (NPI) assuming the further rapid development of this industry to the point that the NPE will take 30% of the world energy production by the 20s of the 21 century [1]. But, this forecast was fated to fail.

According to the IAEA data [2], 449 nuclear power generating units with the total rated output power (netto) of 392 GW were operated and 60 nuclear power generating units (60.5 GW) were under construction in the world by 2017. According to the data as of 2016, the NPE contribution to the power generation is 5%. At that, the NPPs produced 2476 bln kWh in the world or 11% of the world production (the peak was in 1996 – 18 %), while the fossil fuel thermal plants produced more than 65%. And in Russia, the nuclear energy part in the total power production is 16% and it will increase to 20% by 2020 according to the IES RAS forecast [3].

Despite the recession of 2008-2009 and great uncertainty in the perspectives of the further economy development, the world power consumption keeps growing, mainly due to developing countries, and this tendency will continue for decades at least.

The basis of the world's modern nuclear power industry (NPI) is the thermal reactors (TR) with uranium fuel in the open nuclear fuel cycle mode (ONFC). The fresh raw material for the TR fuel is natural uranium containing 0.7% of the fertile uranium (U-235); herewith, the nuclear fuel (NF) is
manufactured out of enriched uranium which contains up to 4-5% U-235. The NF wastes in the ONFC are the spent nuclear fuel (SNF) and depleted uranium in the concentrating production piles. While considering the approximate annual flows of nuclear materials in the ONFC, one can see that generation of 1 GW(e) requires to extract 200 t of natural uranium used for production of 20 t of uranium fuel which, in turn, gives 20 t of SNF and 180 t of concentrating production wastes.

Technological base of LWR constituting the base of the world NPI is sufficient for the expected level of NPP construction (till 2050) but its potential for solution of long-term energy problems is limited as the technical safety level does not meet the principal requirement to the large-scale NPI – prevention of accidents requiring population evacuation (Three Mile Island – 1979; Chernobyl – 1986; Fukushima – 2011).

The “old” NPI technological platform on the base of thermal reactors has the following endemic problems:

- Low efficiency of the extracted natural uranium utilization;
- Lack of environmentally acceptable handling of LLHLRW (minor actinides, etc.);
- Risk of use of fissile materials circulating in the NFC for military or terroristic purposes.

The global NPI is slouching through a recession during the last 30 years. The maximum part of NPPs in the world power generation, 18%, was reached in the early 90s. Now, it is reduced down to 10.7% (figure 1) [2]. The forecasts of the recognized power organizations reflects possible decrease of this part down to one-digit level.

![Figure 1](image1.png)

**Figure 1.** The NPP part in the power production.

Commissioning of new NPP power units for the last 10 years is something equal to decommissioning and less than commissioning of the alternative energetics capacities (figure 2) [2]. The principal barrier for development of the modern NPI is its competitive ability underpinned by the safety problem. Attempts to solve the safety problem by development of additional active protection means resulted in decrease of NPI competitive activity as compared with the organic energetics.

![Figure 2](image2.png)

**Figure 2.** Number of commissioned and decommissioned PU.

2. **Need for the new technological platform (NTP): CNFC with fast neutron reactors**
Fast neutron reactors of inherent safety are designed to overcome the existing obstructions. The best fuel for FR according to the set of characteristics is the mixture of natural U-238 and plutonium (Pu). During Pu fission in the reactor, the new Pu is accumulated in fuel due to FR physics in the quantity equal or exceeding the quantity of the burnt initial Pu as a result of excess neutron capture by nucleuses of natural Uranium-238.

SNF reprocessing and return of accumulated Pu and unburnt uranium into the FR fuel cycle enables to reduce the need for natural uranium by 100 times and to reduce the weight of heavy nucleuses in high-level wastes (HLW) by 10 times.

Advantages of the CNFC over the open NCF involve minimization of resource and RW flows. Due to use of U-238, the CNFC with FR increases the useful fuel resources base by 150 times approx. as compared with the ONFC and draws the NPI to the foreground position in the total resource power balance.

The optimum alternative of the NPI development strategy is switch to two-component structure of the nuclear power industry on the basis of thermal and fast reactors with nuclear fuel cycle closure. Switch to the CNFC in the transition period of the two-component NPI allows to halt rate of SNF accumulation produced in thermal reactors and increase of costs for their handling. Replacement of one TR by FR:

- eliminates production of 1000 tons of WWER SNF (17 tons/year x 60 years) and costs for their storage till reprocessing (384 thous. RUB/t/year in 2015 in the SC);
- increases the commercial product (Pu) output by 15 times at reprocessing (as there is only 1% of Pu in WWER SNF and 15% in FR SNF).
- Usage of reprocessed products for commissioning of FR and CNFC is the effective way to solve the problem of already accumulated WWER SNF:
  - one new FR can recover all SNF for the whole service life of one WWER;
  - replacement of thermal reactors with the capacity of 10 GW by the fast reactors almost completely solves the problem of accumulated Russian WWER SNF (~10 thous. tons), and also gives economic grounds for its reprocessing.

According to our opinion [4], the following capacities of FR will be required for recovery of the current Pu resources:

- energy plutonium at the “Mayak” PE warehouse (40 t of Pu) - 4 GW of FR;
- all accumulated WWER SNF in the RF (10 thousand t of SNF with 100 t of Pu) - about 10 GW of FR,
- former weapon-grade Pu (34 – 50 t) – 3 – 5 GW of FR,
- stock of 600 ÷ 700 kt U nat controlled by “Rosatom” give 600 ÷ 700 t of Pu after burning in WWERs – 60 ÷ 70 GW of FR (at most).

The SNF volume does not appear to be critical at the existing level of SNF accumulation. At the first stage of CNFC implementation, it is effective to use the accumulated stocks of former weapon-grade and energy Pu:

- even at the stage of 2030 ÷ 2040, (4 GW of FR) it allows to clear considerably (or even fully) the “Mayak” PE warehouse and to eliminate costs for further Pu storage;
- engagement of former weapon-grade Pu in the CNFC enables usage of its energy potential.

The requirements intended to overcome the problems of the modern NPI in the area of safety, raw material base, nuclear wastes, non-proliferation and efficiency were developed in Russia at the end of the 20th century for the first time and presented in the “Strategy of the Russian nuclear power industry development in the first half of the XXI century” approved by the country Government (hereinafter referred to as the “Strategy-2000”) [5].

The countries designing nuclear energy technologies formulated the requirements to the new 4th generation reactors under the largest GENERATION-IV International Forum organized at the beginning of the century [6]. Four out of six technologies selected for joint development are different technologies of FR and CNFC.
The user requirements to the innovative NPI systems which meet the sustained development principles were defined under INPRO, the other largest IAEA international project [7]. INPRO researches also confirmed importance of FR and CNFC technologies development, especially for the countries which have large NPP pool or plan large-scale NPI development. At the same time, many countries with small NPP pool prefer TRs of the 3+ generation.

We can underline the following key development milestones for conception of CNFC with FR in Russia:

- 2000 - Strategy of the Russian nuclear power industry development in the first half of the XXI century.
- 2010 - the FTP “Nuclear power technologies of a new generation for the period of 2010-2015 and projected till 2020”.
- 2012 - “PRORYV” Project Direction (under “NPING” FTP).

3. Requirements to NTP

The following requirements to the NPI NTP were determined taking into account restrictions of the “old” technological platform:

- NPI occupational safety - prevention of accidents requiring population evacuation can give the opportunity for large-scale development of the nuclear power industry;
- Environmental safety of NFC - solution of problems associated with LLHLRW handling (MA etc.) and SNF accumulation may eliminate restrictions associated with public acceptance of the NPI;
- Political neutrality of NFC - engineering support of non-proliferation regime may eliminate restrictions associated with political acceptance of the NPI;
- Stable fuel supply of NPI - CNFC may become the basis for long-term provision of NPI (for thousand years) by fuel raw material resources;
- NPI competitive ability.

The main objective of the NTP occupational safety is prevention of accidents in NPPs and other NFC facilities requiring population evacuation. It is necessary to perform the following in order to achieve this objective:

- To eliminate reactive accidents (acceleration on instantaneous neutrons) which may require population evacuation.
- To eliminate accidents with loss of heat removing which may require population evacuation.
- To eliminate fires and explosions at NPP which may require population evacuation.

It is necessary to reduce the reactivity charge in order to eliminate acceleration on instantaneous neutrons. It may be achieved by means of:

- compact fuel for the nuclear reactor core with zero reactivity charge for burning out (NF equilibrium composition),
- small full negative temperature effect of reactivity (1-3%).

The following should be used in the RF design to meet the requirements for the NTP concerning heat removing accidents:

- RF air exchanger;
- Natural coolant circulation with heat removal through the RF air exchanger;
- Decrease of nuclear reactor core hydraulic resistance in order to increase natural coolant circulation;
- Coolant level difference in order to maintain forced flow (for example, at de-energization);
- Passive devices of emergency protection on the basis of temperature operating principle.

In turn, fires and explosions in the RF with radioactivity emission should be eliminated by physical and chemical properties of the coolant and constructional materials which do not interact with environment (air and water) in explosion or fire hazardous manner with hydrogen emission.
Safety of LLHLRW disposal for hundred thousands and millions years gives rise to well-founded doubts. Maintaining the balance between the radiation hazard of disposed RW and uranium raw materials extracted from mines, it is possible to avoid significant changes of natural level of radiation and biological hazard. The NTP ecological safety is aimed at the socially acceptable handling with LLHLRW (MA etc.) and prevention of SNF accumulation. There are the following methods to achieve this aim:

- Prohibition against disposal of RW containing environmentally significant quantities of LLHLRW.
- Decrease of the stored TR SNF quantity and prevention of FR SNF accumulation.
- RW isolation.

It is necessary to use the following methods in order to achieve the stated objectives:

- Processing of TR and FR SNF;
- MA transmutation (in power producing reactors, in special recombiners);
- RW disposal.

One of the NPI NTP objectives is elimination of political restrictions caused by possible use of fissile materials circulating in NFC for military and terroristic purpose. This objective may be achieved by the following ways:

- Elimination of weapon-grade plutonium production in power reactor blankets (for countries not included in “nuclear club”).
- Elimination of “excess” plutonium production in nuclear reactor core.
- Elimination of pure Pu extraction during spent fuel reprocessing.
- Minimization of plutonium residence time outside RF during its circulation in the NFC.

The NTP uses the following means to achieve these objectives:

- BN-1200 with BRC ≈ 1 (compact NF);
- BR-1200 with BRC ≈ 1 (compact NF);
- At water processing of FR SNF: the improved water scheme in PT-1 plant and the water scheme in the PDF;
- Hybrid processing of FR SNF;
- the NFC near plant.

The economically acceptable natural uranium stockpiles are already consistent with the demands of the nuclear power industry on the basis of the old technological platform at expected variants of its development. The main objective of the NTP raw consistency - long-term provision of the NPI (for thousand years) by the fuel raw material resources. This objective may be achieved by:

- Full reproduction of fissionable nuclides in the reactor core;
- Proceeding to the closed NFC.

This objective is achieved by the following means:

- Fast reactor with BRC ≈ 1 (BN-1200, BR-1200);
- Processing of SNF;
- NF fabrication out of the products of SNF processing and natural (or waste) uranium.

The key factor of extensive nuclear power industry development in Russia and in the world is its competitive ability as compared with other power generation types. “Proryv” PD offers the following solutions of this problem:

- Removal and simplification of some safety systems in the NPP;
- Reduction in consumption of materials by RF design simplification;
- Reduction of fuel factor;
- reduction in expenses for transportation - plant nuclear fuel cycle.

4. The key results of development and establishment of the NTP engineering elements under “Proryv” PD

Seven main designing solutions are offered for implementation of the RF occupational safety [8]:
• the equilibrium reactor core of the fast reactor which enables minimization of reactivity margin for fuel burnup and almost prevents acceleration by instantaneous neutron;
• the compact mononitride fuel ensuring implementation of the reactor core without uranium blanket;
• the wide core cage maintaining the natural circulation at the level sufficient for afterheat removal;
• the integral reactor facility packaging which ensures isolation of coolant leaks within the RF case and provides conditions for effective natural circulation;
• heavy liquid metal coolant which enables implementation of the wide cage and eliminates the positive void reactivity effect;
• the lead coolant quality support system which enables usage of the heavy coolant in the high power fast reactors;
• usage of ambient air as the final coolant at natural and circulating afterheat cooling in the high power RF.

The key element of the RF occupational safety is lead coolant and compact nitride fuel. Lead is advantageous because it is high boiling and chemical and radiative low active material. Lead physical properties ensure installation of the wide fuel element cage in the RF nuclear reactor core. The lead polonium activity is by 1000 times less as compared with Pb-Bi alloy. The proximity of the main physical and chemical processes running in the circuits with the lead and lead-bismuth coolants was experimentally confirmed. This fact allows to use the experience acquired at lead-bismuth coolant validation for studying of the lead coolant [9].

By now, the following results were achieved within “Proryv” PD concerning Pb coolant technology:
• The process procedure of the lead coolant technology system operation was developed concerning “BREST-OD-300” reactor facility.
• The system equipment structures were developed (DAK, the mass exchange apparatus, the coolant filter, the hydrogen in air detector, the aerosol filters).
• The coolant quality control tool (DAK) passes the acceptance trials.
• The full-scale mockup of the gas handler was tested successfully.

Usage of nitride fuel in high power producing reactors allows to take the advantage of the reactor core with BRC~1 and the corresponding fuel cycle: small reactivity margin for fuel burnup, fuel self dependence, no need to separate uranium and plutonium, and also the necessary feedback parameters which are critical for the RF safety (ratios and reactivity effects).

The following basic differences between nitride and metallic compact fuel may be determined:
• the nitride fuel has high density and thermal conductivity (1.4 and 10 times higher as compared with oxide);
• the metal has high theoretical density but its density is decreased due to necessity to alloy it (Zr) and to increase sponginess in order to decrease swelling and to increase creeping;
• phase transitions of the metal fuel and especially its interaction with the steel shells resulting in low-melting eutectic formation stipulate small reserve till breakdown in the accidents involving temperature increase, or require coolant cooling;
• the relative disadvantage of the nitride fuel is neutron absorption in the reaction 14N(n,п)14C resulting in some deterioration of neutron balance and formation of carbon 14C with long half-life (may be compensated by replacement by 15N).

Analysis of MNUP-fuel and elaboration of its production technology are performed in the laboratory units on the following sites:
• ARSRIM – samples, fuel and fuel assemblies of BN-600, MIR, BOR-60;
• ARSRITP – samples, fuel and fuel assemblies of BOR-60 (beginning of manufacture – 2016);
• NRRI – samples with MA, fuel, fuel assemblies and EFA of BOR-60
Organization of FA and EFA production for BN-600 (up to 12 FA/year) on the test facilities located on the SICP:

- KEU-1 is the MNUP-fuel experimental technology (up to 200 kg/year);
- KEU-2 is implementation of the MNUP-fuel industrial engineering (since 2016).

Under the ongoing ambitious program of MNUP-fuel testing, 18 EFAs are set for irradiation in the reactor BN-600, and irradiation of 10 EFAs has been already finished. All fuel assemblies remained leakproof.

9 demountable EFAs are set for irradiation in the reactor BOR-60 and irradiation of 5 EFA has been already finished.

The reactor “MHP” finished irradiation of the instrumented fuel assembly consisting of 7 FA with the in-core monitoring detectors of fuel center temperature, gas pressure under shell and fuel column elongation.

FR SNF processing for unburnt uranium and plutonium recycling allows to solve the problem of the NPI wastes providing that the effective methods of different LLHLRW elements are selected, for example:

- Cm recycling in fuel is not practical, it is better to extract Cm and to store it till total decomposition into plutonium.
- Np recycling within NF results in slight deterioration of fuel properties and fully permissible;
- Am recycling scheme requires detailed optimization according to the performance indicators. In the form of tablet fuel, it is better to use heterogeneous burning-out or burning-out in the special fast reactor.

The mixed technology of FR SNF processing P (RN process) enables the following [4]:

- to reprocess the SNF with short holding time and high burning-out,
- to support non-proliferation regime,
- to provide FM losses at the level of ≤ 0.1 %,
- to derive products suitable for fuel fabrication,
- to ensure low volumes of HLW,
- to provide extraction of Am and Cm and their separation.

The PP for all list of equipment handling the PDEC RW were developed under “Proryv” PD [4] including:

- the packaged units for high temperature HLW reprocessing;
- induction slaggy KM meltdown with actinide reextraction;
- pyrochemistry induction meltdown of LRW and HLW in the equipment with “cold” crubicles (may produce glassy or mineral-like matrixes);
- ILW impregnation treatment plant (for the whole range of technological and non-technological LRW of ILW category);
- the plant of filter material hypersonic cleaning of FM.

“Proryv” PD uses two main engineering solutions for implementation of NFC political neutrality objective:

- pyrochemical reprocessing of the fast reactor SNF to shorten SNF holding time before its reprocessing and to prevent emission of pure plutonium during its reprocessing,
- fast reactors without blanket to prevent weapons-grade plutonium production.

It should, however, be noted that it is impossible to solve the problem of non-proliferation of fissile materials circulating in the NFC using only technological solutions.

5. Conclusion

Today, it could be considered as theoretically proven, calculated and experimentally justified that such requirement to the reactor as the BRC ab.1 which may be met by using the massive nitride uranium and plutonium fuel (MNUP-fuel), allows to increase significantly the safety level of the fast reactors
as compared with the fast reactors using the MOX-fuel with the BRC substantially smaller than 1 [10 - 12].

‘Proryv” project direction ensures the leadership of the State Atomic Energy Corporation “Rosatom” in:

• Construction of the RF with inherent safety (deterministic elimination of accidents requiring population evacuation);
• Development of dense MNUP-fuel effective for fast neutron reactors;
• Final solution of the issues associated with SNF accumulation and radiation equivalent handling of RW;
• Establishment of the first pilot demonstrational energy complex with FR and CNFC technologies in the world (PDEC).

The future of Russian nuclear power industry and its sustainable development are associated with establishment of the two-component nuclear power industry and switch to the closed fuel cycle.

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