**Nuclear non-proliferation regime and export of fast neutron reactors with A closed fuel cycle**

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**Abstract**

Currently, the world society recognizes serious environmental problems with anthropogenic impact on the environment and almost does not dispute the main source of its pollution. However, the hope that growing demand of world economies for electricity can be provided by so-called alternative energy sources - solar and wind installations is illusory.

At the same time, the world's existing nuclear power industry consisting of more than 80% of light-water reactors of various capacities also cannot solve this problem as well. The real solution to the energy problem while preserving the climate and achieving the UN Sustainable Development Goals can only be large-scale nuclear energy based on fast neutron reactors (FNR) with a closed nuclear fuel cycle (CNFC). However, the development of such large-scale nuclear energy could create potential risks to the international nuclear non-proliferation regime and may complicate the IAEA's safeguards implementation in non-nuclear-weapon states operating such nuclear power systems.

The report using the example of the BREST reactor as part of a pilot demonstration energy complex being built in Russia will show that these potential risks can be reduced due to the technical features incorporated in the design of such nuclear system. In particular, the absence of separation of uranium and plutonium during reprocessing leads to a high level of radioactivity of the new fuel obtained from the reprocessed one providing self-protection from unauthorized use.

The report will also discuss elements that can be included in the design of the facility that promote the application of IAEA safeguards, including the availability of an automated system for accounting for nuclear materials, as well as online measurements of flows of nuclear materials to ensure the necessary accuracy of measurements of nuclear materials in bulk form.

The report will show that the results of the analysis based on the developed models can make it possible to conclude that the inherent technological elements of such a nuclear system are sufficient to reduce the potential risk of nuclear proliferation.

Based on this, the report will conclude that the future export of FNR with CNFC from Russia with an initial load of fresh fuel and technological processes developed to the best levels will create minimal potential risks to nuclear proliferation, and the use of such nuclear power systems in peaceful nuclear activities of states will contribute to their economic and technological development without negative impact on the environment.

1. INTRODUCTION

 Currently, the society recognizes serious environmental problems and almost does not dispute the main source of environmental pollution due to the extraction and burning of hydrocarbon energy sources. Only nuclear power can provide modern civilization with environmentally friendly energy at the level of tens of billions of tons of oil equivalent without oxygen consumption and environmental pollution; no other energy industry can cope with the tasks of providing energy on such a scale and environmental cleanliness.Environmentally friendly renewable energy sources, for example, solar or wind, are not able to produce energy on such a scale due to the low density of the energy flow [1, 2].

 Energy carriers are the main commodity on international markets, the struggle for access to which is the main source of many years of tension in the Middle East, which is associated with the most acute international problems, such as, for example, in the case of the construction of the Nord Stream-2 gas pipeline. One of the ways to solve the problem of energy supply is to use nuclear energy, which should replace the burning of hydrocarbons. «The development strategy of nuclear energy in Russia until 2050 and prospects for the period up to 2100» [3] considers that the fast neutron reactors (FNR) and closed nuclear fuel cycle (NFC) will become the basis of energy security and environmental safety of Russia after a transition period of ~ 50 years with the simultaneous existence of fast and thermal reactors.

 Speaking at the Millennium Summit in 2000 at the UN, Russian President Vladimir Putin sad that it is necessary to reliably block the ways of the spread of nuclear weapons. This can be achieved, among them by excluding the use of enriched uranium and pure plutonium in peaceful nuclear energy. He continued that the burning of plutonium and other radioactive elements provides the prerequisites for a final solution to the problem of radioactive waste. It opens fundamentally new prospects for a safe life to the world. It follows from this that the sustainable development of mankind can rely on nuclear energy on a new technological platform. Now the Russian Federation and China have already made significant progress in this direction in their research and practical implementation. State Corporation Rosatom has already started the construction of BREST reactor, which is the first experimental fast-neutron reactor with onsite closed NFC, in Seversk, Siberia. In accordance with the RIA Novosti correspondent reports[[1]](#footnote-1), “in Seversk, the construction of the world's first new generation power unit BREST-OD-300 has started at the site of the Siberian Chemical Combine (SHK) of the Rosatom State Corporation as part of the Year of Science and Technology. In a solemn atmosphere with the participation of the leadership of the Russian nuclear industry and the Tomsk region, the pouring of the first concrete into the foundation began”.

In the coming decades, it is possible to start exporting fast neutron reactors with closed NFC to non-nuclear-weapon countries. The export of fuel cycle facilities together with a fast-neutron reactor is not relevant at the initial stage. Most countries are unlikely to consider it acceptable to have a closed fuel cycle on their territory, deal with waste management, up to their final disposal and additional imports of depleted uranium. Therefore, at the initial stages, it is possible to implement a simplified export option with the return of used fuel to the exporting country for reprocessing, as is currently being done with used fuel from thermal reactors. The scale of exports will inevitably increase, expanding the access of new countries to nuclear technologies for reprocessing of used fuel and to plutonium.

Fulfilling the non-proliferation regime is one of the most important issues for such export [4, 5]. Below, the main components of nuclear non-proliferation regime are considered, and the effective barriers preventing nuclear proliferation are presented. To be fair, all plutonium available nowadays is bred in specialized thermal-neutron reactors. No events evidencing the switching of the power reactors to the undeclared operation have been recorded [6].

1. Proliferation Risks

The proliferation risks occur if the importing state possesses:

* facilities for enrichment (separation) of uranium isotopes;
* facilities for plutonium extraction from the irradiated fuel; and
* facilities for storage and handling of the extracted plutonium with isotopic content of 238Pu<20% and highly enriched uranium (235U>20%).

These proliferation risks might be reduced or eliminated by introduction of technical barriers (on the example of the BREST reactor as part of a pilot demonstration energy complex) such as:

* non-separation of uranium and plutonium in solution during the reprocessing which is limited largely to removing the fission products from the uranium-plutonium mixture;
* absence of the uranium enrichment stage in NFC;
* initial fuel loading is based on natural/depleted uranium mix with plutonium obtained after reprocessing of UNF from PWR; and
* high radioactivity of the fresh fuel fabricated from the reprocessed used nuclear fuel (UNF) because Am, Np, and some amount of Cm characterized by high radioactivity (~50 Ci/kg at 1% of the fission product residual in the fuel ) remain in the new fuel for transmutation.
1. BREST reactor

BREST fast-neutron reactor with nitride uranium-plutonium fuel and lead coolant is constructed for a specific “onsite” closed nuclear fuel cycle. The main features of BREST technology allow creating the following technical barriers for possible violations of nuclear non-proliferation regime:

* dense thermal conductive fuel based on (U-Pu-MA)N;
* lead coolant, chemically inert when contacting water or environmental air;
* absence of plutonium breeding zones; and
* closed nuclear fuel cycle without enrichment or extraction of fissile isotopes.

The important feature of the fuel cycle is the absence of the uranium enrichment stage which could be used for fuel manufacturing. Thus, the criterion satisfying non-proliferation principles is transformed just into the requirement to radiochemical reprocessing technology of the irradiated fuel, i.e. do not allow separating uranium and plutonium at any stages of the reprocessing process. Physical features of fast-neutron reactor allow for incomplete fuel purification from fission products during reprocessing (the content of residual fission products is 1% to 5%). Moreover, americium, neptunium, and some amount of curium remain in the fuel for transmutation. The above impurities in the fuel, all together, contribute to a high radioactivity level (about 50 Ci/kg for 1% of fission products remaining in the fuel) and are intrinsic physical (radiation) protection of the fuel from diversion, including unauthorized removal. Radiochemical reprocessing without plutonium extraction mainly involves fuel purification from fission products. In addition, the entire cyclic fuel turnover is concentrated in the reactor building and the adjacent fuel cycle building, which is very important in terms of increasing the protection of the material from unauthorized use.

1. Features of modern export of power reactors

Export of fast reactors, as well as closed nuclear fuel cycle facilities is not restricted by the RF or international legislation but it will be evidently adopted by the global community only in compliance with the nuclear non-proliferation regime and efficient application of IAEA safeguards during the entire life cycle of a fast neutron reactor itself and the nuclear fuel cycle facilities. Barriers providing technical difficulties for the importing state, which has decided to use the received facilities and technologies in violation of the nuclear non-proliferation regime, will provide an important addition to the IAEA safeguards.

Since most of the countries in the world became the States Parties of the Nuclear Non-Proliferation Treaty and signed appropriate safeguards agreements with the IAEA, it seems practical to consider the fast reactor export only to those countries. These states have committed to the application of the IAEA safeguards to all the nuclear materials in all peaceful nuclear activities so that the materials cannot be diverted for production of nuclear weapons or some other nuclear explosive devices. Correspondingly, IAEA, according to the agreement, is authorized and obliged to apply its safeguards to all the fissile materials in all peaceful nuclear activities on the territory of the state or under its jurisdiction to exclusively verify absence of such diversion. In this context, the key word is “all” and thus encouraging IAEA to verify both correctness and completeness of the state declarations, i.e. to detect the undeclared nuclear materials and activities.

However, export reliability and compliance with the non-proliferation regime can be improved by the measures that contribute to the IAEA safeguards implementation, including enhancement of the nuclear material control and accounting system, higher measurement accuracy for the bulk nuclear materials. These measures should become an integral part of the design. It is known that the existing measurement errors in the nuclear material control and accounting system during the closing of material balance procedure which is, carried out at technological facilities, especially with high throughput, raise questions about the value of material unaccounted for from the point of view of possible diversion of fissile materials from production line. It is important to assess the existing measurement errors and determine the required time intervals and labor costs so that the nuclear material control and accounting system will possibly permit to make a timely conclusion about an attempt to divert significant quantities of plutonium in the fuel reprocessing and, consequently of compliance/incompliance with the nuclear non-proliferation regime. In this case, the nuclear material physical protection system may become an extra barrier but its resistance on the importing state territory should be additionally studied.

As for the undeclared nuclear activities and clandestine works to design nuclear weapons, IAEA is currently analyzing open information sources to detect the indicators of these activities. The conduct of nuclear tests, as practice has shown, can be detected, since the mechanisms for detecting secret nuclear tests are known and sufficiently worked out.

Thus, additional conditions would be created for the export of fast neutron reactors with the “onsite” nuclear fuel cycle implemented as part of the Russian technology and equipment with initial fresh fuel loading and technological processes developed to the best levels.

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