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

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**Abstract**

Currently, societies of the world recognize their serious anthropogenic impact on the environment, and they do not dispute pollution as the main source. The current hope is that growing demand of world economies for electricity will be met by alternative energy sources - solar and wind installations, which is illusory. At the same time, the world's existing nuclear power industry consisting of mainly light-water reactors (LWR) 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 met with large-scale nuclear energy based on fast neutron reactors (FNR) in 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 that operate these nuclear energy systems.

This report uses the BREST pilot demonstration energy complex being built in Russia to show the potential reduction in nuclear proliferation risks through the incorporation of technical features. In particular, not separating uranium and plutonium during reprocessing leads to high levels of radioactivity in the new fuel to providing a barrier from unauthorized use. Other features of the energy system promote the application of International Atomic Energy Agency (IAEA) safeguards, such as the use of an automated system for nuclear material accounting, as well as online measurements of nuclear material flows s to ensure the measurements of nuclear materials in bulk form meet safeguards requirements. The analysis of the BREST energy complex, based on the developed models, make it possible to conclude that the inherent technological elements of such a nuclear energy system are sufficient to reduce the potential nuclear proliferation risk.

In conclusion, the future export of a Russian nuclear energy system based on a FNR in a CNFC with an initial load of fresh fuel will have minimal nuclear proliferation risk. A State can use these nuclear energy systems for peaceful nuclear energy activities, which will contribute to the State’s economic and technological development without negatively impacting 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. However, there is one environmentally friendly nuclear power industry capable of providing modern civilization with energy at the level of ten billion 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 large scale and with 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 suppliers are a main commodity on international markets. The struggles for access to this commodity is a source of tension in the Middle East. Energy supply is associated with acute international problems, for example, the construction of the controversial Nord Stream-2 natural gas pipeline. One of the ways to solve the problem of energy supply is to use nuclear energy, which could 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 United Nations, 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 declared in the Russian Federation. 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 will be possible to export FNR with CNFC to non-nuclear weapon States. The export of fuel cycle facilities together with a FNR is not relevant at the initial stage. Most countries are unlikely to consider it acceptable to have a CNFC on their territory, deal with waste management up to its final disposal, and imports of depleted uranium. Therefore, at the initial stage, it may be possible for the exporter 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 light water reactors of Russian design in some options. The scale of exports will inevitably increase, allowing new countries to access nuclear technologies for reprocessing used fuel.

Fulfilling obligations of the non-proliferation regime is one of the most important issues for completing nuclear technology exports [3, 4]. Below are the main components of nuclear non-proliferation regime and effective technical barriers for preventing nuclear proliferation. To date, there is no recorded evidence of power reactors switching to the undeclared operation for breeding plutonium [6].

1. Proliferation Risks

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<80% and highly enriched uranium (235U>20%).

The implementation of the following technical barriers could reduce the above risks:

* non-separation of uranium and plutonium in solution during the reprocessing which will result in 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 used nuclear fuel (UNF) from pressurized water reactors (PWR); and
* using high radioactivity of the fresh fuel fabricated from the reprocessed UNF, (characterized by Am, Np, and some amount of Cm which have high radioactivity [~50 Ci/kg at 1% of the fission product residual in the fuel]); these highly radioactive elements remain in the new fuel for transmutation.

The above examples are incorporated into the BREST FNR and demonstration energy complex.

1. BREST reactor

The design of the BREST FNR, using uranium-plutonium nitride fuel and lead coolant, is for a specific “onsite” CNFC. The main features of the BREST technology are the incorporation of the following technical barriers to prevent possible violations of the nuclear non-proliferation regime:

* dense thermal conductivity fuel based on (U-Pu-MA)N [where MA is minor actinides]);
* lead coolant, chemically inert when in contacting with water or environmental air;
* absence of plutonium breeding zones; and
* closure of the nuclear fuel cycle without enrichment or extraction of fissile isotopes.

An important feature of the fuel cycle of the BREST technology is the absence of the uranium enrichment which usually exists in fuel manufacturing for PWR. Thus, the criterion satisfying non-proliferation principles is transformed just into the requirement to radiochemical reprocessing technology of the irradiated fuel, which does not allow separation of pure uranium and pure plutonium at any stages of the reprocessing process. A physical feature of the BREST technology is the incomplete fuel purification from fission products during reprocessing of used fuel (the content of residual fission products is 1% to 5%). Moreover, americium, neptunium, and some amount of curium remain in the new fabricated 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 is an intrinsic physical (radiation) protection barrier to prevent diversion of the nuclear fuel, including unauthorized removal. Radiochemical reprocessing of used fuel without pure plutonium extraction mainly involves purification of fission products from the fuel. In addition, the entire cyclic fuel turnover is concentrated in the reactor building and the adjacent fuel recycling 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 FNR, as well as CNFC facilities is not restricted by the RF or international legislation and could only be accepted by the global community if it is in compliance with the nuclear non-proliferation regime and it supports efficient application of IAEA safeguards during the entire life cycle of the energy complex including the FNR and associated nuclear fuel cycle facilities. The technical barriers in the BREST energy system, (FNR and associated fuel recycling facilities,) is an important addition to the IAEA safeguards for non-proliferation; and supports States wanting to import these energy systems while meeting their obligations in the nuclear non-proliferation regime.

Most of the countries in the world are States parties to the Nuclear Non-Proliferation Treaty and have also signed appropriate safeguards agreements with the IAEA, therefor it seems practical to consider only exporting BREST FNR to these States. These States agree to only pursue the peaceful use of nuclear technologies and show commitment 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, the 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.

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 nuclear materials especially in bulk form. These improvements should become an integral part of the design. Measurement accuracy is important during the closing of material balance periods and can be significant for facilities with especially high throughput of nuclear material. The accuracy of measurements for determining the value of material unaccounted for (MUF) can raise questions regarding the possible diversion of fissile materials from a production line. It is important to assess the existing measurement errors, determining the required inventory time intervals and associated labour costs so that the nuclear material control and accounting system can make a timely conclusion about an attempt to divert significant quantities of plutonium in the fuel reprocessing and, consequently of compliance/noncompliance with the nuclear non-proliferation regime. The nuclear material physical protection system is an extra barrier to nuclear material diversion. Each State wanting to import these energy systems should be specifically studied for non-proliferation prior to the import/export.

The IAEA is currently analysing open-source information for indicators to enhance detection of undeclared nuclear activities and clandestine operations for developing nuclear weapons in a State. The conduction of nuclear tests connected with nuclear weapons, as practice has shown, can be detected, since there are mechanisms for detecting nuclear tests.

In conclusion, implementation of additional measures in support of nuclear non-proliferation for the export of the “onsite” nuclear fuel cycle as part of the Russian technology and equipment with initial fresh fuel loading in the reactor could support States needing environmentally friendly and reliable energy.

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