**SPECIFIC FEATURES OF THE EXPORT OF**

**RUSSIAN TECHNOLOGIES OF FAST REACTORS**

**AND A CLOSED NUCLEAR FUEL CYCLE**

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**Abstract**

At the present stage of development there has actually been a consensus in the nuclear world community on the dominant role of fast reactors in the future large-scale nuclear power. In addition to the main role of these reactors in providing nuclear power with fuel in the imminent shortage of natural uranium resources, an important aspect of their use is also the solution of the ever-increasing volumes of spent nuclear fuel from thermal reactors. The technology of Russian fast sodium reactors has been successfully demonstrated and is currently entering the stage of its commercialization. Currently, there are two fast power reactors BN-600 and BN-800 being operated in Russia. In this regard, there may be in the future a real possibility of exporting Russian fast reactors to countries that do not possess such technology. For the first time, this topic was proposed for discussion in the report of the Russian participants at the International IAEA conference FR13, then the discussion was continued at the FR17 ​​conference. Somewhat later, statements by the leadership of the State Atomic Energy Corporation «ROSATOM» followed that Russian technologies of fast reactors and closed nuclear fuel cycle could enter international markets in 10-15 years as an export product of the Russian nuclear power industry. All this determines today the need to analyze the potential export of nuclear power plants with fast reactors, including nuclear fuel, as well as closed nuclear fuel cycle facilities, taking into account both the technical and economic indicators of such power units, and the existing system of International supply regime in the field of nuclear energy technologies. The report discusses the main features of fast reactor technology in comparison with the existing technology of exported thermal reactors in the context of the implementation of the International supply regime in the nuclear power field.

## 1. INTRODUCTION

At present, Russia is the recognized world leader in terms of the number of nuclear power units being built abroad. In the long term, it is planned to significantly expand the scale of International business, which is reflected in the target indicators of ROSATOM and its organizations. In particular, the portfolio of foreign orders of the State Corporation «ROSATOM» for a 10-year period is about $140 billion by the end of 2020. The foreign business portfolio of «ROSATOM» includes 35 power units in 12 countries [1]. Currently, 2 nuclear power units in Russia are under construction, and up to 10 units of Russian designs are being constructed abroad: in Belarus, Bangladesh, China, Egypt, Finland, Hungary, Iran, India, Turkey [2].

The key competitive advantage of «ROSATOM» in the global nuclear power technology market is an integrated offer for the provision of a range of services, including construction, operation and maintenance of nuclear power plants throughout the entire life cycle of up to 60 years or more, adopted for new projects with VVER-1200 reactors. At the same time, it is envisaged to provide foreign nuclear power plants with «fresh» fuel and, in some cases, return spent nuclear fuel (SNF) to Russia for technological temporary storage and reprocessing. As a responsible supplier of nuclear technologies, «ROSATOM» actively promotes the development of nuclear energy in other countries, especially in newcomers, with strict observance of International norms and agreements in the field of nuclear nonproliferation.

Today we can say with great assurance that in the medium term, and possibly for a longer period, the technology of Russian VVER reactors will remain commercially attractive at the world market. In the long term, the main problems of these reactors - the limited resource base of natural uranium and ever-increasing volumes of spent nuclear fuel - remain unresolved unless the existing technological structure of the domestic nuclear power industry is changed.

The growing demand for energy, especially in developing countries, will inevitably lead to a significant increase in the nuclear capacity of the thermal reactor fleet and, as a consequence, to the aggravation of problems associated with the limited reserves of relatively cheap natural uranium and the increasing rates of accumulation of spent nuclear fuel from thermal reactors. And then the competitiveness of nuclear power, while conservation its current technological structure, will increasingly depend on the efficiency of using natural uranium and solving the SNF problem.

At the present stage of development, in addition to the main role in providing fuel in a shortage of natural uranium resources, as was considered in the past, the role of fast reactors in management of ever-increasing volumes of SNF from thermal reactors is one of the first of importance. In this regard, it is quite logical that the topic of fast reactors occupies a central place in the International projects of INPRO and the International Forum Generation IV.

In modern Russia, the strategic direction in nuclear energy is the continuation of the development of fast reactor technology and a closed nuclear fuel cycle (NFC). At present, this activity continues in two main directions: BN-type reactors using sodium coolant and a centralized location of the closed nuclear fuel cycle infrastructure, and BREST-type lead-cooled reactors and on-site placement of the closed nuclear fuel cycle infrastructure.

An additional area of activity in fast reactors can be considered the development of a modular SVBR reactor for small-scale power generation. The technology of such a fast reactors using lead-bismuth coolant was demonstrated when used in Soviet submarines.

To date, the maturity of the technology of fast reactors with sodium coolant has been demonstrated at the industrial level, including many years of experience in operating nuclear power plants with BN-350 (1972-1999), BN-600 (since 1980) and BN-800 (since 2016) fast reactors. The nuclear power plant operating today at the Beloyarsk NPP is the only one in the world where energy production is carried out using BN-600 and BN-800 fast reactors. It can be considered that at present the technology of fast reactors BN has entered the stage of its commercialization. The finalization of the BN-1200 reactor design, related mainly to its economic parameters, has entered its final phase. In terms of its economic parameters, the BN-1200 is close to the same as for the VVVE-1200 thermal reactor. In accordance with the layout of electric power facilities in the country, approved by the decree of the Government of the Russian Federation in 2017, the construction of a power unit with BN-1200 reactor at the Beloyarsk site is envisaged [3].

In the Breakthrough project, the development of BREST fast reactors with lead coolant and on-site location of a closed nuclear fuel cycle infrastructure continues. This technology is considered promising for the future, but to date it has not been demonstrated at a power plant, so it is premature to prove its technological maturity. To demonstrate this technology, in the aforementioned layout of electric power facilities in the country the construction of power unit with an experimental demonstration reactor BREST-OD-300 at the Seversk NPP at the Siberian Chemical Combine (SCC) is envisaged. At the same site, it is planned to build a pilot demonstration energy complex with the entire infrastructure of the on-site closed nuclear fuel cycle [4].

Taking into account the achievements of Russia in the field of fast reactor technology, the State Atomic Energy Corporation “ROSATOM” began to raise questions and discussions about the possibility of exporting in the future fast reactors and closed nuclear fuel cycle enterprises [5, 6].

## 2. BASIC INTERNATIONAL LEGAL DOCUMENTS TO ENSURE NUCLEAR NON-PROLIFERATION

### 2.1. Treaty on the Non-Proliferation of Nuclear Weapons

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) is the fundamental document to maintain the nuclear non-proliferation regime [7]. Under Article I, each nuclear-weapon State, member of the NPT, undertakes not to transfer nuclear weapons or other nuclear explosive devices to anyone, and not directly or indirectly grant control over such weapons or explosive devices, as well as not in any way assist, encourage or induce any non-nuclear-weapon State to manufacture or otherwise acquire such weapons or other nuclear explosive devices or to control over such weapons or devices.

In accordance with Article II, each non-nuclear-weapon State, member of the Treaty, undertakes not to accept from anyone the transfer of nuclear weapons or other nuclear explosive devices or direct or indirect control over such weapons or devices; not manufacture or otherwise acquire such weapons or devices, and not seek or receive any assistance in the manufacture of such weapons or devices.

In accordance with Article III.1, each non-nuclear-weapon State, member of the Treaty, undertakes to accept IAEA safeguards for all source or special fissionable material in all peaceful nuclear activities on the territory of that State, under its jurisdiction or control elsewhere. Under Article III.2, each State, member of the Treaty, undertakes not to provide source or special fissionable material, or equipment or material specially designed or prepared for the processing, use or production of special fissionable material, to any non-nuclear-weapon State for peaceful purposes, if the source or special fissionable material is not under the safeguards envisages by Article III.1. Article III.4 obliges each non-nuclear-weapon State, member of the NPT, to conclude a safeguards agreement with the IAEA, either individually or jointly with other States, within 18 months after the date of the depositing of documents about ratification or accession to the Treaty.

Article IV affirms the right of all States, members of the NPT, to develop research, production and use of nuclear energy for peaceful purposes, and to facilitate to the maximum extent possible participation in the exchange of equipment, materials or information on the peaceful uses of nuclear energy.

### 2.2. International Atomic Energy Agency safeguards

Safeguards applied by the International Atomic Energy Agency (IAEA) are an important element of the global nuclear non-proliferation regime [8]. Under a comprehensive safeguards agreement, they are used to verify that a State is complying with its obligation to accept safeguards on all nuclear material in all its peaceful nuclear activities, and to verify that such material is not diverted to nuclear weapons or other nuclear explosive devices. In this regard, a technical objective is defined as the timely detection of a diversion of significant quantities of nuclear material to the production of nuclear weapons or other nuclear explosive devices or to unknown targets and the suppression of such diversion due to the risk of early detection. International and other nuclear non-proliferation instruments that form the basis of the IAEA safeguards system or are otherwise closely related to the application of IAEA safeguards include the IAEA Statute, contracts and supply agreements requiring verification of compliance with non-proliferation obligations, basic safeguards documents, safeguards agreements and related protocols; and guidelines related to the implementation of IAEA safeguards.

### 2.3. Additional protocol

The Additional Protocol is not a stand-alone agreement, but rather a protocol to a safeguards agreement providing additional means of verification [9]. In particular, it significantly enhances the IAEA's ability to verify the peaceful uses of all nuclear material in States with comprehensive safeguards agreements. A protocol to a safeguards agreement (or agreements) is concluded between the IAEA and a State or group of States based on the provisions of the Model Additional Protocol. A Model Additional Protocol providing for measures to enhance the effectiveness and efficiency of IAEA safeguards that could not be applied under the legal authority provided by safeguards agreements. The protocol was approved by the IAEA Board of Governors in 1997. The IAEA uses the Model Additional Protocol to negotiate and conclude additional protocols and other legally binding documents.

### 2.4. Nuclear Suppliers Group Guidelines

The Nuclear Suppliers Group (NSG) Guidelines relate to the export policies and practices of NSG member States with respect to transfers nuclear material, equipment and technology, and nuclear-related equipment, materials, software and appropriate dual-use technology to non-nuclear-weapon States for peaceful purposes. Dual-use technology is a technology that is technically applicable to both nuclear and non-nuclear use and is subject to certain delivery conditions, as such technology can make a significant contribution to nuclear explosive device activities) [10]. The guidelines are currently consisted in two parts.

### 2.5. Zangger Committee Guidelines

The Zangger Committee Guidelines on Export - principles agreed upon by a group of States, members of the NPT to clarify the obligations of States under Article III.2 of the Treaty with respect to export for peaceful purposes to non-nuclear-weapon States of nuclear material and equipment or material specially designed or prepared for the processing, use or production of special fissionable material [11]. The Guidelines are based on a «Trigger List» of source and special fissionable material and agreed equipment and materials specially designed or prepared for the processing, use or production of special fissionable material, the export of which requires the application of IAEA safeguards to the corresponding source or special fissionable material. The Zangger committee is not an IAEA committee.

### 2.6. Plutonium Management Guidelines

The Plutonium Management Guidelines are principles to ensure the safe and efficient handling of stored plutonium in accordance with International obligations, including those under the NPT and with safeguards agreements with the IAEA [12]. The Guidelines describe, among other things, the nuclear material accountancy system, physical protection measures and International transfer procedures for plutonium subject to the Guidelines. They further contain the detailed information for publication by States, members regarding plutonium management, including annual declarations of their civilian separated plutonium total content and storage sites and estimates of plutonium content in spent reactor fuel.

### 2.7. Physical protection recommendations

Physical Protection Recommendations are the IAEA recommendations for the physical protection of nuclear material and nuclear facilities, revised and published in 1999 and contained in Ref. [13]. The Convention on the Physical Protection of Nuclear Material, for which the IAEA serves as the depository, establishes International standards, inter alia, for the protection of International shipments of nuclear material and encourages International cooperation on the exchange of physical protection information. The Convention entered into force in 1987 and is reproduced in document [14]. Physical protection includes measures taken by States to prevent or avoid the theft of nuclear material during its use, storage and transportation, and to discourage sabotage of nuclear facilities by subnational groups.

## 3. FEATURES OF FAST NEUTRON REACTORS

The safeguards measures currently applied to exported light water reactors can serve as a basis for the development of a safeguards system that might be will applied to future exported fast reactors. In this case, special attention should be paid to the basic features of fast reactors in comparison with thermal light water reactors [15–18].

### 3.1. Fast reactor fuel

Reactors with a fast neutron spectrum are able to more efficiently use nuclear material due to the recycling of plutonium and the use of uranium-238, which is practically not used in reactors with a thermal neutron spectrum. In the fast neutron spectrum, the microscopic cross sections of materials are small; therefore, the content of fissile isotopes in the fuel of fast reactors is several times higher than in the fuel of thermal reactors. This applies equally to fresh fuel for fast reactors and spent fuel. In addition, some fast reactor projects can use highly enriched uranium (HEU) fuel as a driver fuel. Plutonium and HEU, as well as nuclear fuel based on them, are classified as direct use nuclear material. From the point of view of safeguards and physical protection, such fuel should be given more attention in inspections than uranium fuel for thermal reactors. In turn, unirradiated fuel should be given more attention than irradiated fuel. Therefore, fast reactor facilities will be subject to more frequent inspections involving more measurements and redundant surveillance, containment and monitoring, with the necessary redundancy of appropriate instruments. In addition, the plutonium produced in the blanket has an isotopic composition similar to that of weapons-grade plutonium. Such plutonium contains mainly plutonium-239, having in its composition small amounts of higher isotopes of plutonium and small amounts of plutonium-238. When implementing a closed nuclear fuel cycle, the «fresh» fuel of fast reactors may contain some amounts of minor actinides and fission products. Consequently, in all cases for fast reactors it is necessary to have more accurate measurement methods, including non-destructive testing methods.

At the same time, like in thermal reactors, nuclear materials in exported fast reactors must be subject to an accounting and control system in the form of items, i.e. core fuel assemblies and radial blanket assemblies.

### 3.2. Coolants used in fast reactors

In experimental facilities of fast reactors, liquid metal coolants, including sodium, lead, and lead-bismuth eutectic, have received the greatest justification. Sodium as a coolant has proven itself well in demonstration and prototype installations of fast reactors in a number of countries: Russia, USA, France, Great Britain, Japan, China, and India. The coolant based on the lead-bismuth eutectic was used in nuclear reactors for a series of submarines of the USSR Navy. As for the lead coolant, so far its application has not been demonstrated in practice, as is the case with sodium and with the lead-bismuth eutectic.

Without discussing the advantages and disadvantages of each of these materials used as coolants in developing projects of fast reactors in different countries, including in the projects of the Generation-IV International Forum, it is noted here that the liquid metal coolant differs from water, which is used in light water reactors. , in terms of the application of safeguards measures. The fundamental difference from water lies in the opacity of these materials for the visible spectrum of light rays. Therefore, monitoring and control of the assemblies loaded into the fast reactor, including radial blanket assemblies (if any), to identify the assemblies by reading their identifiers is a problem that must be solved by developing new methods to «see» objects under the liquid metal layer.

### 3.3. Design features of fast reactors

The core of fast reactors, like light water reactors, consists of a set of fuel assemblies (FA) and a system of control and protection rods (CPS). At the same time, fuel assemblies of fast reactors are distinguished by smaller dimensions and an overall lower weight than fuel assemblies of light water reactors.

Fuel assemblies of the sodium-cooled fast reactor core (BN reactor designs) usually have lower and upper end screens containing depleted uranium dioxide (as in the BN-600 reactor). In the BN-800 reactor and in the BN-1200 project, a so-called sodium plenum is formed instead of the upper end screen followed by axial boron shield. The core in a fast reactor can be surrounded by a radial blanket with fertile material (usually depleted uranium dioxide). On the periphery, there are cells of the in-reactor storage of irradiated fuel assemblies are located, which serve for temporary, relatively short holding of spent fuel assemblies before unloading from the reactor.

In designs of fast reactors with lead coolant, developed in the "Breakthrough" project there are no end parts in the core fuel assemblies, as well as a radial blanket and cells of the in-reactor storage of fuel assemblies, similar to the design features of light-water reactors.

Some designs of fast reactors may contain layers or subzones of fertile material in the core. For example, an axial interlayer for leveling the heat release field along the height of the core and increasing the breeding ratio. Or subzones containing minor actinides for their burning out in the fast neutron spectrum, or other materials, such as burnable absorbers, various targets for the production of isotopes, etc., which will require the development of new methods of non-destructive testing and measurements and new calibration materials for these methods.

### 3.4. Fast Reactor Refueling Procedure

It should be emphasized that the procedure for refueling in fast reactors is fundamentally different from that in light water reactors. Further, the existing experience of refueling in a fast reactor with a sodium coolant is briefly described using the practical example of the BN-600 reactor [19]. With a high degree of probability, it can be assumed that the same refueling procedure in the main details will be applied in fast reactors with a lead coolant.

In the BN-600 reactor, the assemblies are located under a layer of liquid sodium, therefore, the extraction of spent assemblies and the installation of fresh assemblies in their positions takes place in a completely closed reactor, in contrast to light-water reactors, for which the top cover of the reactor is removed during refueling and the visible access to the core opens. In this case, all operations in the core for unloading spent assemblies, loading fresh assemblies are visually monitored by appropriate stationary and portable video cameras. For fast reactors, such visual control is impossible, since there are no video surveillance devices inside the reactor vessel and all operations with assemblies in a closed and hermetically sealed reactor are carried out «blindly», guided by signals from the corresponding sensors of the refueling machine.

In the upper part of the BN-600 reactor there are large and small rotating plugs (eccentric relative to each other). A column with control and protection systems is mounted on the small rotating plug, as well as refueling mechanism with a collet-type grip. The rotating mechanism is equipped with a hydraulic seal made of a special fusible alloy. In the normal condition, it is solid, and in preparation for refueling, it is heated to the melting point, while the reactor remains completely sealed, so that the release of radioactive gases from the reactor is practically excluded.

The refueling process includes several steps. The ultimate goal is to install fresh assemblies from the drum of fresh assemblies into the required core cell, and for spent assemblies unloading assemblies from the core into the appropriate drum. First, the grip is aimed to one of the assemblies located in the in-reactor storage of spent assemblies, takes it out of the cell it and transfers it to the unloading elevator. Then the assembly is lifted into the transfer box and placed in the drum of spent assemblies, from where, after washing (cleaning with steam from sodium residues) it is transferred to the water pool.

In the next step, the refueling mechanism removes one of the spent core assemblies and transfers it to the in-reactor storage. After that, the required assembly is removed from the drum of fresh assemblies (into which fresh assemblies were previously loaded from the storage of fresh assemblies at the NPP), it is installed in the elevator for loading fresh assemblies, which moves it to the refueling mechanism. The last step is the installation of this fresh fuel assembly into the vacated cell in the core. During refueling the operator does not have direct visual feedback when performing all the above steps, and is guided only by the indicators of the column rotation angle sensors with an refueling and gripping mechanism (positioning accuracy is less than 0.01 degrees), as well as by the efforts of removal and setting assemblies from and to the appropriate cells. The same steps are performed to make refueling radial blanket assemblies.

As can be seen from the summarized scheme of refueling, fresh fuel assemblies loaded into the drum become «invisible» to the operator, including all further operations with them until the spent fuel assemblies are unloaded from the spent fuel assembly drum and transferred to the spent fuel pool (similarly for radial blanket assemblies).

It follows from this, that since it is impossible to control visually the operations making with assemblies inside the reactor, it is necessary to provide reliable and redundant surveillance, measurements, and monitoring for the process of loading fresh assemblies into the drum for fresh assemblies and for the process of unloading spent assemblies from the drum of spent assemblies. Any violations and undeclared actions committed at the initial stage of loading fresh assemblies into the drum will be impossible to determine and fix during further operations. Therefore, this initial phase is very important to prevent the diversion of nuclear materials and the misuse of the facility.

In subsequent developments and projects of fast reactors (for example, in the design of the BN-1200 reactor), the refueling scheme was improved, mainly by means of the improving of some operations and decreasing the metal consumption of the refueling equipment of the reactor, but these changes did not affect the operations that are fundamental from the point of view of accounting and control of nuclear materials.

### 3.5. Closed nuclear fuel cycle of fast reactors

The principal purpose of fast reactors is to organize a closed nuclear fuel cycle due to the breeding nuclear fuel and its multiple recycling, which significantly increases the energy potential of natural uranium in comparison with thermal reactors. In practice, this means that nuclear power plants can operate and make progress during a historically significant period of time without limitation of the available fuel resources. Thermal reactors use natural uranium inefficiently, leaving ever-increasing volumes of spent nuclear fuel, which many countries consider nuclear waste designated for long-term isolation from the environment. At the same time, spent fuel contains a huge energy potential that is currently not being used. And only with the commissioning of fast reactors can this energy potential be used, including in a two-component nuclear power system with thermal and fast reactors operating in a common closed nuclear fuel cycle.

When organizing a closed nuclear fuel cycle, in addition to the fast reactors themselves, it is necessary to have the entire developed infrastructure of the NFC, in which the key enterprises are facilities for fabrication / refabrication of nuclear fuel and for SNF reprocessing with appropriate radioactive waste management and transportation systems. For each of these enterprises, appropriate approaches to the implementation of the IAEA safeguards measures should be developed.

Developments in the field of fast reactors show that during fabrication / refabrication of fresh fuel using recyclable materials, it is possible to assume that a certain proportion of fission products are present in this fuel, for example, remaining during not full purification of plutonium. At present, the issues of transmutation of minor actinides (MA) by adding a certain amount of MA to the fuel of fast reactors during its fabrication (transuranic fuel) are also being studied.

Currently, the IAEA inspectors have direct contact with fresh fuel assemblies of light water reactors, due to their weak radioactive radiation. The presence of minor actinides and possibly fission products in the fresh fuel of a fast reactor can significantly complicate handling such a fuel for accounting and control purposes. It is necessary to study whether direct contact of the IAEA inspectors with such a fuel will be possible, or whether it will be necessary to use any kind of protective equipment or some kind of remote modes and operations for its verification, measurement and sealing. It will also require the development of new methods of non-destructive testing and corresponding systems of instruments, instrumentation and calibration samples.

## 4. SAFEGUARDS SYSTEM ON THE EXPERIMENTAL FAST BRIDER-REACTOR «MONJU»

The Monju facility is a relatively large and fairly modern fast reactor with a thermal power of 714 MW(th) and an electric power of 280 MW(e) with a sodium coolant and MOX fuel. An important design feature of this reactor was the presence of radial blanket with fertile material. It is important to note that such a fast reactor project was implemented in Japan, a non-nuclear-weapon country. The reactor adopted the most up-to-date approach to International safeguards system at the time, including measures in connection with the implementation of the Additional Protocol, as well as measures to control the environment in the vicinity of the facility. This facility can serve as a starting point for the development of modern safeguards measures for other fast reactor projects, including those for export [20].

The safeguards approach for the Monju reactor was developed in accordance with the IAEA document INFCIRC / 153, a typical comprehensive safeguards agreement concluded between Japan and the IAEA. The Monju reactor was designed with safeguards in mind and was arguably the first fast reactor in the world to implement the state-of-the-art Safeguard by Design concept. The goal of International safeguards at the Monju reactor is the timely detection of a MOX fuel diversion. The target amount of diverted MOX fuel for detection represents one significant quantity of plutonium (1 SQ), which is 8 kg of plutonium in the MOX fuel. Safeguards also was applied to uranium at the reactor, but to a lesser extent.

The timeliness of detection a possible diversion depends on whether the plutonium is in unirradiated "fresh" or irradiated "spent" fuel. In the first case, the goal of timeliness of detection is one month, in the latter case three months. The first term essentially dictates the need for monthly inspections carried out by the IAEA inspectors on the place, that is, at the facility.

The safeguards approach for Monju was based on the traditional approach applied to all MOX-fueled reactors under the IAEA safeguards agreement, which includes:

* Determination of material balance areas (MBA) for nuclear material accountancy;
* Determination of key measurement points (KMP) to measure the flow and inventory of nuclear material;
* Define strategic positions for containment and surveillance (C/S) and other verification measures;
* Nuclear material accountancy through analysis of operational records and State reports;
* Annual Physical Inventory Verification (PIV) - usually during reactor shutdown for refueling (every 6 months);
* Verification of internal and external transfers of nuclear material;
* Statistical Nuclear Material Balance Assessment to determine material unaccounted for (MUF); MUF includes measurement uncertainties, process losses and, if applicable, also diverted material. (If the MUF value exceeds the measurement error, the IAEA inspector can state that the material has been lost);
* Routine (monthly) interim inventory verification to detect in a timely manner possible diversion of nuclear material;
* Verification of information on the design of the facility;
* Checking the operator's measuring system.

In addition to the safeguards measures and functions outlined above, additional features have been provided for Monju to ensure the reliability of safeguards applied to MOX fuel, including:

* Reliable physical protection of fuel assemblies’ storage sites;
* Advanced redundant containment and surveillance systems consisting of several types of sensors, gamma detectors, neutron detectors and surveillance cameras. Digital data from these systems is viewed by an ultra-fast imaging system for semi-automatic detection of changes in monitored areas;
* Continuous, maintenance-free, custom-designed non-destructive testing systems to track the movement of MOX fuel in a reactor and determine, by interpreting gamma and neutron radiation that the fuel is not mock-up, but real fresh MOX fuel, blanket assemblies or spent MOX fuel.

In addition to these specific reactor safeguards activities, the following requirements have also been identified:

* Advance provision of information on the design of the facility by the national authorities (at the time of the decision by the national authorities to build or modify a nuclear facility);
* Sampling and analysis of environmental samples by the IAEA to detect traces of radioactive contamination to verify the operator's declared use (and previous use) of the facility.

Additional measures applied at Monju in accordance with the Additional Protocol to the Japan-IAEA Safeguards Agreement that have come into force include:

* Submission by Japan of additional information declaring all nuclear facilities and nuclear activities in the country, which is updated annually;
* Annual submission by Japan of information regarding the manufacture of nuclear related equipment (such as reactor vessels) and research related to the nuclear field (such as research related to fast reactors);
* The IAEA has the right to provide complementary access to nuclear sites and areas of proposed nuclear research at short notice to detect undeclared nuclear materials and/or activities;
* The IAEA is authorized to use visual surveillance, environmental sample collection and use of radiation detection devices to detect undeclared nuclear materials and/or activities.

## 5. ADDITIONAL SAFEGUARDS MEASURES FOR EXPORTED FAST REACTORS

When considering new designs of fast reactors in the light of historical and reference facilities, based on the results of this study, it can be concluded that the measures and procedures currently used for safeguards for exported light water reactors, including those of Russian design, can serve as a basis for developing measures and safeguards procedures for future exported fast reactors. At the same time, it is necessary to take into account the approach which was previously used for the Monju fast reactor in Japan. However, safeguards experts have identified additional technical issues that need to be further developed for fast reactors. These additional technical needs are as follows [20]:

* It is necessary to develop new methods of non-destructive assay (NDA) to more accurately measure the content of plutonium and actinides in fresh assemblies with transuranium fuel (TRU fuel) received at nuclear power plants with fast reactors and in spent assemblies sent out from nuclear power plants. NDA measurements for TRU fuel are complicated by the presence of minor actinides in the fuel and the high neutron and gamma radiation fields of the spent fuel. These methods should be capable of detecting partial defects in fuel assemblies in accordance with the current IAEA criteria and have a measurement accuracy of about +/- 5% for plutonium and other actinides. To demonstrate these methods, samples of TRU fuel materials for future fast reactors should be prepared in advance for the purpose of validating new NDA methods and calibrating related instruments;
* Many of these NDA methods or systems will need to be developed to track in-line all movements of fresh and spent fuel, from the receipt of fresh fuel at the NPP, the movement of fuel within the NPP site, and the shipment of spent fuel from the NPP. These methods should allow for remote transmission of data in order to «remotely monitor» the object to provide more effective safeguards;
* Increased use of automated, unattended remote monitoring systems is needed to collect data on the safeguards at the facility, cooperating with the facility owner / operator and national authorities to handle proprietary information. A more comprehensive automated and integrated data collection and analysis system needs to be developed to track processes and in real-time surveillance images to support verification of nuclear material transfers, inventory and facility operational status;
* An active dialogue with the IAEA should be established to negotiate a more flexible interpretation of the IAEA Department of Safeguards SGTS Policy No.20 on the sharing of facility’s equipment for safeguards needs. The current interpretation is very restrictive and limits the IAEA's use of the wide range of operational instruments available at the facility due to the perceived need to obtain independent safeguards conclusions from these instruments. It is suggested that this strict interpretation should only be applied to instruments of primary importance to safeguards, and not to the wide range of instruments relevant to the operation of the facility which may still provide additional safeguards data;
* Cooperate closely with the facility owner / operator and national authorities to try to incorporate safeguards and safeguards equipment requirements into the concept design at the earliest stages of the facility conceptual design;
* Make the inspection regime more efficient by using unplanned short notice inspections, applying a «statistical process control» approach to verifying reprocessing plants, rather than routinely systematically verifying all major transfers of plutonium-containing materials. For this approach to be effective, the facility operator would need to announce in advance the major activities associated with nuclear material. It would also be more efficient and effective to apply this approach at the site-wide level, not just at the facility level;
* Current approaches to safeguards for fast reactors are highly dependent on storage areas and transport routes for fresh and spent TRU fuel. The current conceptual designs need to be reviewed to ensure that such secure storage and transfer areas for nuclear material are designed to facilitate stable operations and to provide nuclear inventory control points that will facilitate to verify nuclear material inventory.

Since the most fast reactors are at various stages of design maturity and have not currently reached the commercial deployment stage, developers and designers are well positioned to incorporate safeguards into reactor designs. These possibilities and considerations may include [21]:

— Advance provision of information on the design of the facility before its final revision;

— Discussion in advance of the possibilities of applied safeguards measures;

— Submission by the State of additional information on nuclear facilities and activities related to the nuclear fuel cycle;

— Enhanced safe storage of plutonium, HEU or TRU fuel;

— Advanced backup systems for surveillance, containment and monitoring;

— Continuous automatic (no human presence) non-destructive assay to monitor the movement of fuel, allowing to distinguish between assemblies and rods with fissile and fertile materials, as well as objects made of non-nuclear material;

— The safeguards implications of using fuels containing minor actinides are not well understood and will require extensive R&D;

— Clear separation of all hot cells and handling equipment operating with fuel element from the rest of the reactor equipment so that they can be placed under more stringent safeguards measures without affecting the status of other reactor equipment dealing with item control and accountancy (FAs).

References

1. FINMARKET, News. http://www.finmarket.ru/news/5405241, 04.02.2021.
2. PPs under construction. https://rosatom.ru/production/design/stroyashchiesya-aes/, 13.01.2021.
3. Order of the Government of the Russian Federation № 1209-р, 9 June 2017. <http://publication.pravo.gov.ru/Document/View/0001201706190028?index=17&rangeSize=1>.
4. Construction licence issued for Russia's BREST reactor [https://www.world-nuclear-news.org/Articles/Construction-licence-issued-for-Russias-BREST-reac. 11.02.2021](https://www.world-nuclear-news.org/Articles/Construction-licence-issued-for-Russias-BREST-reac.%2011.02.2021).
5. Avrorin E.N., Chebeskov A.N. Fast reactors and nuclear nonproliferation In Proc. of FR13 International Conference, Paris, France, 4-7 March 2013.
6. Avrorin E.N., Gulevich A.V., Simonenko V.A., Chebeskov A.N. Fast neutron reactors, fuel cycles and problem of nuclear non-proliferation. In Proc. of FR17 International Conference, Ekaterinburg, Russia, 26-29 June 2017.
7. Treaty on the Non-Proliferation of Nuclear Weapons. [https://www.un.org/ru/documents/decl\_conv/ conventions/npt.shtml](https://www.un.org/ru/documents/decl_conv/%20conventions/npt.shtml).
8. IAEA Safeguards Glossary. 2001 Edition. [https://www-pub.iaea.org/MTCD/Publications/PDF/ Glossary\_russian.pdf](https://www-pub.iaea.org/MTCD/Publications/PDF/%20Glossary_russian.pdf).
9. Additional Protocol. <https://www.iaea.org/topics/additional-protocol>.
10. Nuclear Suppliers Group Guidelines. [http://www.export-nn.ru/eksportyeram/eksportnyy-kontrol/gruppa-yadernykh -postavshchikov/](http://www.export-nn.ru/eksportyeram/eksportnyy-kontrol/gruppa-yadernykh%20-postavshchikov/).
11. Zangger Committee Guidelines. <http://www.ved.gov.ru/komitet_cangera/>.
12. IAEA INFCIRC 549. Communication received from certain member states concerning their policies regarding the management of plutonium.
13. Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities(INFCIRC/225/Revision 5), IAEA 2011.
14. Convention on the Physical Protection of Nuclear Material. <https://www.iaea.org/sites/default/files/> infcirc274r1\_rus.pdf, МАГАТЭ 1980.
15. Lvova E.M., Chebeskov A.N. Analysis of Attractiveness of Nuclear Materials as Applied to the On-site Fuel Cycle of Inherently Safe Fast Reactor. Nuclear Engineering and Technology, v.3, issue 3 (2017), pp. 224-230.
16. Kagramanyan V.S., Chebeskov A.N., Dekusar V.M., Gurskaya O.S. Solving the problem of thermal reactor SNF in a two-component nuclear power system. In Proc. Of the 11th International scientific-technical Conference “Safety, effectiveness and economics of nuclear power”. Moscow, Russia, 23-24 May, 2018.
17. Klinov D.A., Gulevich A.V., Chebeskov A.N. Export potential of Russian fast reactors and technologies closed nuclear fuel cycle. In Proc. of the V International scientific-technical Conference “Innovative of projects and technologies of nuclear power”. Moscow, Russia, 2–5 October, 2018.
18. Gulevich A.V., Dekusar V.M., Chebeskov A.N., Kuchinov V.P., Voloshin N.P. The possibility of export of fast reactors in the conditions of the nuclear non-proliferation regime. In Jornal “Atomnaya Energiya”, v. 127, issue 3, p. 171-175, 2019.
19. The ballad about fast neutrons: a unique reactor of the Beloyarsk NPP. <https://www.popmech.ru/science/9816-ballada-o-bystrykh-neytronakh-unikalnyy-reaktor-beloyarskoy-aes/>.
20. Durst P.C., Therios I., Bean R., et al. Advanced Safeguards Approaches for New Fast Reactors PNNL-17168 December 2007.
21. International safeguards in the design of nuclear reactors. IAEA Nuclear energy series No. NP-T-2.9, Vienna, 2014.