**EXPORT POTENTIAL AND**

**COMMERCIALIZATION CONDITIONS**

**OF FAST REACTORS CONSIDERING**

**NON-PROLIFERATION ITEMS**

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**Abstract**

Fast reactors (hereafter, FR) are a unique technological solution, which permits to provide enhancement of efficiency of uranium resource efficiency within the framework of closed fuel cycle. The FR is attractive less as a power reactor than as a basis to close the nuclear fuel cycle for potential customers. The Treaty on the Non-Proliferation of Nuclear Weapons, International Atomic Energy Agency’s safeguards system and Guidelines for the Export of Nuclear Material, Equipment and Technology of the Nuclear Suppliers Group do not prohibit directly export of FR, high-enrichment fuel for FR or for plants of irradiated nuclear fuel reprocessing, which are also necessary to close nuclear fuel cycle. However, the FR export potential is limited because of the possibility to use the FR with breeding ratio more than 1 to produce weapon-grade plutonium even if a country-recipient has no power unit with the FR for spent nuclear fuel reprocessing at the moment of delivery. The present paper considers possible export scenarios for FR-based power units considering nuclear weapon non-proliferation requirements and obligatory conditions of this export implementation. Considering the results of analysis of limitations, alternative scenarios of FR export potential realization providing full use of distinctive features of the FR technology while meeting the non-proliferation requirements are proposed.

1. INTRODUCTION

At present, the need to use FR is acquiring the greatest urgency. Despite the fact that the number of FR designs is limited, research on the design, construction and further commissioning of industrial FR is ongoing in a number of countries with leading positions in the field of nuclear power. There are plans not only to expand the fleet of commissioned FR, but also to expand the range of applications of FR.

The use of FR together with thermal neutron reactors within the framework of dual-component power industry will enable to solve the problems related to production and reprocessing of nuclear fuel, ecology of spent nuclear fuel and radioactive waste storage, non-proliferation of nuclear material, and economic viability of nuclear power.

The export potential of FR is limited due to the unique technical characteristics and peculiarities of this type of reactors, which may be used for non-peaceful purposes. The IAEA has limited experience in applying safeguards to FR. At the same time, FR may clearly be used in international cooperation for the management of nuclear materials that reveals the export potential of FR not only as a facility but also as a technology.

1. DEVELOPMENT OF FR DESIGNS

Characteristics of FR should not be inferior to thermal neutron reactors in deployment as a source of energy taking into account requirements of the market. FR designs have reached maturity due to optimization of technical solutions that give an opportunity to expand and improve their range of capabilities. FR have evolved from a niche product, as it was in the 20th century, to a full-fledged competitor of thermal neutron reactors.

The technologies used in FR designs are quite complex and require developed competencies in nuclear technology, scientific personnel, specialized test facilities, and a high level of industrial technology development, including coolant purification technologies among others.

FR development programs exist in a limited number of countries, including the United States, France, the People’s Republic of China (PRC), India, South Korea, Japan, and the Russian Federation. The United States, France, Japan, and South Korea are developing FR designs in order to develop new technologies that have not previously been applied to this type of reactors. In the medium term, these designs will remain at the research and development stage to try-out certain process engineering solutions. Among others, the United States is developing Traveling wave reactor-prototype, which is scheduled to be licensed by 2030; France is developing a molten salt reactor based on fast neutrons, which is scheduled to be commissioned after 2050 [1]. The PRC and India already have successful experience with experimental FR designs and are developing commercial prototypes.

The Russian Federation has reference experience in building and operating FR. The BN-600 reactor plant has been in commercial operation for more than 30 years. In 2015, the Beloyarsk Nuclear Power Plant held a power start-up of an experimental production unit with the BN-800 reactor plant, and in 2020 the first 18 serial fuel assemblies with uranium-plutonium fuel were loaded into the BN-800; and currently the BN-800 core is one third full with innovative fuel. A picture of the Beloyarsk Nuclear Power Plant is shown in Fig. 1 [2].

In 2014, the detailed design of the BN-1200 reactor plant was developed by Afrikantov OKBM JSC, as well as the detailed design of the turbine plant and key materials of the power unit design [3]. In 2016, research and development work was completed to justify the baseline design of BN-1200. In 2017, during the Generation IV International Forum, the BN-1200 concept was officially accepted and approved as meeting the requirements for Generation IV FR, including high economic requirements [3]. Research and development work is currently underway to substantiate the technical solutions accepted in the BN-1200 reactor plant design, including with respect to the justification of the safety and competitiveness of the power unit. A picture of the BN-1200 reactor plant is shown in Fig. 2 [4]. Technical characteristics of the upgraded BN-1200 reactor plant are presented in Table 1 in accordance with the optimization of specific elements of the design [3].

The PRC is already fruitfully working with France on technology development and production of uranium-plutonium fuel, cooperating with Terrapower (USA) on the development of Traveling wave reactor-prototype based on fast neutrons, and taking an active part in the Generation IV Forum.

Taking into account the complexity of the technology, FR can offer opportunities for large-scale international cooperation. Thus, on November 6, 2018, as part of the first China International Import Forum EXPO, representatives of the Russian Federation, via State Atomic Energy Corporation “Rosatom”, and representatives of the PRC, via China Nuclear Power Industry Corporation, signed a package of executive contracts for the implementation of the Chinese CFR-600 fast-neutron demonstration reactor project [5].

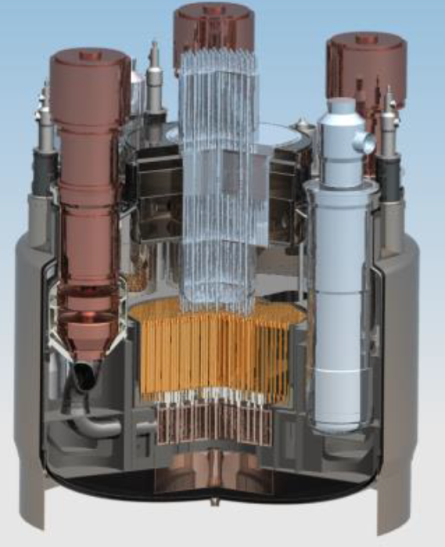
The scope of the project includes, among other things, contracts:

* For delivery of equipment, rendering of training services, installation and adjustment supervision;
* For delivery of Russian computer codes;
* For the examination of the Chinese CFR-600 design.

For the nuclear industry of the Russian Federation, cooperation within the CFR-600 activities is seen as a significant project and its implementation will open the way to future broader cooperation in the framework of a bilateral Comprehensive Program which includes, among other things, cooperation in constructing high-capacity power units in Russia, the PRC and in third-party countries.



*FIG. 1. Beloyarsk Nuclear Power Plant.*



*FIG. 2. BN-1200 reactor plant.*

TABLE 1. TECHNICAL CHARACTERISTICS OF BN-1200 REACTOR PLANT

|  |  |  |
| --- | --- | --- |
| Item | Name | Value |
| 1 | Thermal power | 2,870 MW(th) |
| 2 | Electric power | 1,250 MW(e) |
| 3 | Service life of main equipment | 60 years |
| 4 | Number of fuel assemblies in core | 432 pieces |
| 5 | Breeding ratio | 1.2 |

1. EXPORT OF FR AND IAEA SAFEGUARDS

Business areas, which are classical for the nuclear power industry and focused on foreign markets, include the following scenarios:

* Scenario 1: turnkey construction of a nuclear power plant;
* Scenario 2: supply of certain types equipment;
* Scenario 3: consulting and expert services, including staff training, verification of computer codes, testing using test facilities of the supplier country to try-out own technologies.

The market for commercialization of FR technology under these scenarios is very limited due to the high requirements for the nuclear infrastructure of the host country, including requirements for scientific and personnel support, qualification and competencies of the service personnel, availability of test facilities, and the level of industrial development in the host country. These requirements are now primarily met by the nuclear-weapon states, in the terminology of the 1968 Treaty on the Non-Proliferation of Nuclear Weapons, which have a deployed and long-term nuclear energy development program and nuclear fuel cycle closure program.

It should be noted that there are no explicit prohibitions on the export of FR in international documents, particularly in the Treaty on the Non-Proliferation of Nuclear Weapons (INFCIRC/140), within the IAEA safeguards documents (INFCIRC/153, INFCIRC/207, INFCIRC/540) and the Nuclear Suppliers Group Guidelines for the Export of Nuclear Material, Equipment and Technology (INFCIRC/254/Rev.10, INFCIRC/254/Rev.13). The Russian Federation also has no bans on export of FR from viewpoint of export control [6].

The nuclear-weapon states are not obliged to place FR with breeding blanket under IAEA safeguards. This greatly simplifies the procedure for exporting fast neutron technology from one nuclear-weapon state to another. For example, the cooperation between the PRC and the Russian Federation under CFR 600 project is arranged according to this principle. To ensure the non-proliferation regime during cooperation under scenarios 1, 2 and 3, the states cooperate on the projects within the framework of special intergovernmental agreements. Such agreements may include assurances that the exported articles and the articles produced on their basis:

* Will not be used to produce nuclear weapons or other nuclear explosive devices or for any military purpose;
* Will be provided with physical protection measures at or above the levels recommended by the IAEA;
* Will be re-exported or transferred out of the jurisdiction of the recipient country to any other country only with the prior written authorization of the appropriate authorized body and the national regulatory body of supplying country.

However, this level of bilateral interaction goes beyond cooperation with the Agency. It should also be noted that the nuclear-weapon states have national control over the circulation of nuclear materials, which is just as effective and structured as the IAEA's control.

1. EXPORT OF FR TO NON-NUCLEAR-WEAPON STATES

Although there are no direct restrictions on export and import of fast neutron technologies, export of fast neutron technologies to non-nuclear-weapon states pose additional safeguards challenges. Non-nuclear-weapon states must notify the IAEA of import of technology and equipment, and subsequently place reactor plants under IAEA safeguards in accordance with the Comprehensive Safeguards Agreement. It appears that the export of certain equipment of a nuclear power plant with FR and fuel for them to a non-nuclear-weapon state is possible under the following conditions:

* Non-nuclear-weapon state gives assurances concerning non-exploitation of imported technologies towards nuclear weapons, implementation of corresponding physical protection measures and elimination of export of these technologies to third countries without a permission of a supplying country;
* The recipient country has concluded a full package of safeguards agreements with the IAEA;
* Technical and organizational measures are ensured to implement IAEA inspections;
* The FR are supplied without separation of breeding blanket assemblies;
* No export of fuel cycle technologies is made [7].

From viewpoint of the IAEA safeguards, the main difference between the fuel cycles of thermal neutron reactors and FR is that the fuel cycle of FR contains highly enriched uranium and higher quality plutonium, which can be used to create weapons of mass destruction. In addition, fresh FR fuel, as well as irradiated fuel and breeding blanket assemblies, contain significant quantities of plutonium. Moreover, significant amounts of special nuclear material are contained in FR fuel assemblies at all stages of the nuclear fuel life cycle [7].

At present, there is experience in the application of the IAEA safeguards to the BN-350 reactor, which was operated from 1973 to 1999 in Kazakhstan. Among other things, the international community has accumulated practices of long-term storage of spent nuclear fuel after the decommissioning of BN-350. However, this experience is not sufficient to declare the existence of established procedures and algorithms of applying non-proliferation safeguards to FR.

In general, safeguarding a nuclear power plant with FR is much more complicated than safeguarding a nuclear power plant with thermal neutron reactors. Taking into account the larger amount of nuclear material at the plant and the difficult access to it due to the technological features of FR, and the lack of IAEA equipment to inspect nuclear material under the sodium coolant layer, optimization of IAEA inspection methods and introduction of new types of containment and surveillance measures equipment that enable effective control of nuclear material are needed. An important aspect is controlling the use of the FR not for excessive production of fissile nuclear materials, but for the decontamination and destruction of currently available nuclear materials [8].

The increasing volume of spent nuclear fuel can cause an increase in proliferation risks, including the risk of possible actions by terrorist organizations if nuclear technologies are not properly protected in countries that are just starting to develop nuclear power industry. Large quantities of nuclear materials circulate in the nuclear fuel cycle. At the same time, a few kilograms of material are sufficient to make weapons of mass destruction [9].

Exporting FR without a breeding blanket and without additional fuel reprocessing facilities would negate the attractiveness of the technology as a fuel reproduction facility and as the basis for closing the nuclear fuel cycle. In addition, this scenario would require exporting highly enriched fuel to the host country of the FR, which is also subject to additional IAEA control.

1. REPROCESSING SPENT NUCLEAR FUEL USING FR

Taking into account the complexity of operating FR, when there are equal power and economic parameters of thermal neutron reactors and FR, newcomer countries and countries that do not have a national program aimed at closing the nuclear fuel cycle will be oriented toward purchasing the easier-to-operate thermal neutron reactor option.

At the same time, FR have a number of unique characteristics that make it possible to consider fundamentally new scenarios for commercialization of the FR technology. A key feature of FR is their ability to reprocess spent nuclear fuel. The market for spent nuclear fuel reprocessing services is shaping up due to the growing number of thermal neutron reactors. In the medium term it is planned to build and commission small modular reactors, which will be located in places that are inaccessible to the location of conventional nuclear power plants. In this connection, the demand for nuclear fuel, the quantity of which is limited by the amount of natural uranium mined, is predicted to grow.

In the context of international legal documents, the Nuclear Materials Management initiative shares common elements with the goals of Agenda 21 adopted at the United Nations Conference on Environment and Development. In particular, these goals are stated in Chapters 19, 20 and 22 of that Agenda [10].

In addition to the aforementioned Agenda, the use of FR for reprocessing spent nuclear fuel also meets the goals stated in the Resolution adopted by the UN General Assembly on September 25, 2015 A/RES/70/1:

* Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all;
* Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable;
* Goal 12. Ensure sustainable consumption and production patterns;
* Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development [11].

At the same time, not only thermal reactor fuel, including spent nuclear fuel, but also plutonium accumulated in thermal reactors may be used as a breeding blanket in FR. In particular, it seems possible to recycle high-level waste, minor actinides, such as neptunium, americium, curium, in order to burn them out gradually before disposal. These three elements take several centuries to decay [12]. This is a major obstacle in arrangement of the high-level waste storage. In FR, the minor actinides are subject to transmutation, which subsequently reduces their danger to the ecological balance of the environment. Actinides from several thermal neutron reactors can be burned out in a single FR. Also, reprocessing of spent nuclear fuel in a closed fuel cycle with FR does not require separation of uranium and plutonium [13]. As a result of this fuel cycle, it will not be possible to produce impurity-free plutonium that also increases the non-proliferation level.

At the same time, a large amount of accumulated spent nuclear fuel can already be observed at the beginning of the 21st century. According to the IAEA Nuclear Energy Series document No. NW-T-1.14 Status and Trends in Spent Fuel and Radioactive Waste Management as of December 31, 2013 there have been 370,000 tons of spent nuclear fuel released from nuclear power plants worldwide since 1954. Looking at this figure by region, more than 194,000 tons of spent nuclear fuel have been accumulated in Eastern and Western Europe, more than 46,000 tons in the Far East, more than 121,000 tons in North America, and 5,000 tons in Latin America. Of the 370,000 tons, 121,000 tons have been reprocessed. At present about 260,000 tons of spent nuclear fuel are in storage and will be reprocessed or will remain in storage [14].

The difficult situation with spent nuclear fuel storage in Europe should also be noted. Although Sweden, Finland and France have well-developed programs for spent nuclear fuel storage, European countries find it difficult, due to geographic, economic and political reasons, to set up their own programs for spent nuclear fuel storage. In this regard the European countries are cooperating within the framework of the European Repository Development Organization. Regarding the international cooperation on spent nuclear fuel storage, the IAEA has issued the IAEA Nuclear Energy Series document No. NW-T-1.5 Framework and Challenges for Initiating Multinational Cooperation for the Development of a Radioactive Waste Repository, which, among other things, mentions scenarios for international cooperation in the joint development of spent nuclear fuel storage facilities [15].

In France, which is at the forefront of FR technology development, the existing spent nuclear fuel reprocessing system enables only a single reprocessing, which ultimately reduces the volume of spent nuclear fuel by 6 times [16].

According to the 2019 IAEA Nuclear Technology Review, taking into account that production facilities around the world can reprocess approximately 5,000 tons of spent nuclear fuel per year and are not currently at full capacity, existing capacity is insufficient to reprocess the accumulated amounts of spent nuclear fuel [17].

The implementation of a closed nuclear fuel cycle on the basis of FR can be a solution to the problem of depletion of natural resources and processing of accumulated radioactive waste, as well as their disposal. The transition to a closed nuclear fuel cycle requires the introduction of new fuel handling technologies, including the development and increase in the number of operating FR. The possibility of a closed nuclear fuel cycle may be considered within a single country. However, since fast neutron technologies are initially concentrated in a limited number of countries, it is possible to consider a global scenario of a closed nuclear fuel cycle, in which FR would still be localized within nuclear-weapon states and used to reprocess spent nuclear fuel from foreign countries. In this case we may talk about a closed nuclear fuel cycle at the level of the international system.

1. INTERNATIONAL COOPERATION ON SPENT NUCLEAR FUEL REPROCESSING

FR and their ability to close the nuclear fuel cycle could, in the strategic perspective, become a solution to the problem of spent nuclear fuel accumulation. Usually “closure of the nuclear fuel cycle” is understood as the creation of a dual-component energy system based on thermal neutron reactors and FR within a single country. This is explained, among other things, by the fact that unique technological solutions are protected in the country as proprietary data, imply different approaches and legal regulation, which complicates the process of integrating national technologies of different countries into a single system. From viewpoint of non-proliferation at the national level, fast neutron technologies and the closed nuclear fuel cycle are controlled through a state system of accounting and control of nuclear materials. This determines the discrete and localized distribution of fast neutron technologies in a limited number of countries today. The exchange of information and facilities containing fast neutron technologies takes place in most cases between nuclear-weapon states.

In this regard, it is worth considering the following commercialization scenario, which is alternative to the approaches taken in the commercialization of thermal neutron reactors. Countries that possess fast neutron technology may provide spent nuclear fuel reprocessing services to countries that do not possess the appropriate technology. In this case FR and reprocessing facilities will be located on the territories of states possessing nuclear weapons, and export of the technology itself will be limited to the product of FR operation and production facilities, namely fresh nuclear fuel for thermal neutron reactors. It is also possible to establish international centers to reprocess spent nuclear fuel, which, if the states that possess fast neutron technology agree, might be put under IAEA safeguards similar to the International Uranium Enrichment Center in the Russian Federation [18].

From the viewpoint of non-proliferation safeguards this commercialization scenario has the following advantages:

* The fast neutron technology and spent nuclear fuel reprocessing remain localized within a few countries;
* The main burden of accounting and control falls on the countries that host FR and reprocessing facilities, which already have competent, trained personnel, technical capabilities, and a sufficient level of their development;
* The IAEA monitors export and import transactions regarding the transfer of spent nuclear fuel for reprocessing and the return of compacted waste for storage using known control technologies and proven procedures.

Such an initiative would provide a solution to the global problem of spent nuclear fuel in the long term while significantly reducing the risks of nuclear proliferation.

The market-based principles of the 1997 Kyoto Protocol, which is a supplement to the 1992 UN Framework Convention on Climate Change, may be adopted as a mechanism to implement international arrangements for spent nuclear fuel reprocessing: Cooperating member countries would set targets for spent nuclear fuel reprocessing for the medium and long term. Achievement of the targets will be monitored by designated collective bodies or by the IAEA.

1. CONCLUSION

Commercialization of FR is limited by both the lack of experience and the absence of a tested procedure for placing these reactor types under IAEA safeguards, and their technical peculiarities. The export potential of FR and their promotion in foreign markets is significantly limited compared to the export potential of thermal neutron reactors. The export of a reactor plant with a breeding blanket itself is possible, but only to member states of the Treaty on the Non-Proliferation of Nuclear Weapons which possess nuclear weapons. For non-nuclear-weapon states, import of FR is difficult both from viewpoint of meeting nuclear infrastructure requirements and from viewpoint of meeting the requirements of the international nuclear non-proliferation regime. For the purposes of this regime, the optimal scenario for the commercialization of FR seems to be the creation of centers for reprocessing spent nuclear fuel on the territories of nuclear-weapon states. This scenario may be implemented within the existing international non-proliferation regime by establishing and involving as many countries as possible in the centralized reprocessing of spent nuclear fuel. The relevant IAEA's support in promoting this initiative and the incentives available at the national level to use spent nuclear fuel reprocessing services abroad and to receive fresh nuclear fuel will make it possible to implement this international initiative and solve the problem of spent nuclear fuel.

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