Fast Neutron Reactors, Fuel Cycles and Problem of Nuclear Nonproliferation

E.N. Avrorin[a)], A.V. Gulevich[b)], V.A. Simonenko[a)], A.N. Chebeskov[b)]

[a]Russian Federal Nuclear Center - Zababakhin Institute of Applied Physics, Snezhinsk, Russia
[b]State Scientific Center of the Russian Federation – Institute for Physics and Power Engineering named after A.I. Leypunsky, Obninsk, Russia

Abstract. Problems are discussed with regard to nuclear fuel cycle resistance in fast reactors to nuclear proliferation risk due to the potential for use in military programs of the knowledge, technologies and materials gained from peaceful nuclear power applications. Advantages are addressed for fast reactors in the creation of a more reliable mode of nonproliferation in the closed nuclear fuel cycle in comparison with the existing fully open and partially closed fuel cycles of thermal reactors. Advantages and shortcomings are also discussed from the point of view of nonproliferation from the start with fast reactors using plutonium of thermal reactor spent fuel and enriched uranium fuel to the gradual transition using their own plutonium as fuel.

Keywords: fast reactor, closed fuel cycle, nuclear nonproliferation, physical protection of nuclear facilities and nuclear materials.

E-mail contact of main author: chebes@ippe.ru

1. Introduction

The basis of the current global nuclear power system are light water reactors operating in the open nuclear fuel cycle. In our country it is the VVER-type reactors, which are the basis for ramping up capacity in the coming decades. Russia quite successfully operates in foreign nuclear power markets, actively offering foreign customers nuclear plants with VVER reactors and services in the nuclear fuel cycle (NFC). Many professionals understand now that the improvement of attractiveness of Russian nuclear power plants (NPP) for the domestic use as well as for export will depend on not only the performance on economy, safety, nonproliferation, but also more and more on how the systemic problems of modern nuclear power such as the management of spent fuel (SNF) and raw material provision will be solved. A fundamental solution of these systemic problems is seen in the way of development and transition to the technology of fast reactors and closed NFC. In this regard, the Russian experts discuss the possibility of increasing the export potential of the existing nuclear power technologies and related issues to strengthen the global nuclear nonproliferation regime and physical protection of nuclear materials (NM) [1, 2].

To detect potential nuclear terrorism actions and to implement effective counter-terrorism measures require the creation of robust physical protection of nuclear facilities (NF) and NM. For fast reactors, using nuclear materials with a higher content of fissile isotopes compared with thermal reactors, physical protection measures of NM and the selection of personnel to work with such NM is an important task for today. This fully relates to Russia, taking into account the long-term strategy of the national nuclear power development.

Two major nuclear technologies: uranium enrichment and spent fuel reprocessing are the legacy of military activity, i.e., are "sensitive" and therefore require close attention to effect and assure the nonproliferation of nuclear weapons (NW). Moreover, the situation becomes much more complicated if in addition to the scope of the export potential of fast reactor technologies in the future will involve technology of radiochemical reprocessing and re-fabrication of nuclear fuel, as in the case of fast reactors with the closure of the NFC.

The paper discusses fast reactors and NFC resistance to nuclear proliferation risk due to the potential for use in military programs of the knowledge, technologies and materials gained from peaceful nuclear power applications. This paper addresses also the possible options for launching fast reactors with the use of plutonium obtained from thermal reactors and the use of uranium fuel with a gradual transition to the use of their own plutonium.

2. The role of fast reactors in the sustainable development of civilization

Brundtland Commission Report of 1987 "Our Common Future" warned the world about the urgent need for progress in the field of economic development that could be sustained without depleting natural resources or harm the environment. The report defined sustainable development as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3].
The main objective of sustainable development is to maintain or augment resources (natural, human-made work, as well as human resources or social achievements) for future generations and at the same time to minimize the consumption of non-renewable resources and the prevention of ecosystem overload. The concept of sustainable development was the result of a joint account of three main factors: economic, environmental and social.
Energy is essential for sustainable development. With the continued growth of the population, the economy and the increase in the developing world needs, a substantial increase in energy needs is a fact, even taking into account the ongoing improvement in energy efficiency. The demand for electricity will grow even more rapidly because electricity is simply cleaner, more flexible and more convenient for consumers. Development of nuclear power expands the natural resource base that can be used for energy production, increases capital created by the human labor and with safe handling has almost no effect on the ecosystem. Nuclear energy systems (NES) have the potential to provide a sustainable source of energy with the ability to satisfy any reasonable forecast of global energy needs in a historically significant period in the future using fast reactors and closed nuclear fuel cycle technologies that have already been tested and demonstrated [4].
For the practical implementation of these features, the need is to develop innovative designs of nuclear reactors and advanced fuel cycle schemes that are characterized by increasing security, significantly improved economics, and better use of resources, minimization of radioactive waste (RW), and the promotion of non-proliferation of nuclear weapons purposes [5]. To this end, approximately at the same time, two international projects have been organized: the Gen IV International Forum (GIF) and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). Both international projects have selected fast reactors for the major role to achieve sustainable development.
The start for the GIF was a meeting of senior government representatives of 9 countries in January 2000 to begin the discussion of international cooperation for the development of NES of the 4^{th} generation. An international team, which includes about 100 experts from different countries, analyzed 130 reactor concepts and as a result 6 reactor technologies has been selected for development within the IFG. Out of selected technologies 5 technologies have fast neutron spectrum and are designed to work in a closed NFC.
The following two main objectives in the field of sustainability have set in the development of Generation-IV NES [6]:

- Generate energy sustainably and promote long-term availability of nuclear fuel.
- Minimize nuclear waste and reduce the long-term stewardship burden.

The international project INPRO was established on the initiative of Russian President V. Putin, launched September 6, 2000 at the UN Millennium Summit, and started in 2001 on the basis of the IAEA General Conference resolution of 2000 (GC (44) / RES / 21). The main objectives of this project are to:

- To help ensure that the nuclear power has made a valuable contribution to meet energy needs for sustainable development of humanity;

- To bring together technology holders and users so that they could jointly consider action at the international and national levels, which are required to ensure that nuclear energy sustainability through innovations in technology and / or institutional arrangements.

As in the IFG, in INPRO the major nuclear power technologies –including the technology of fast reactor and the closed NFC to meet the energy needs of sustainable human development are considered [4].

3. Russian achievements in the development of fast reactor technology

Currently, Russia is the only country in the world, which uses fast reactors to generate commercial nuclear energy. This has been achieved thanks to the fact that only in our country have the necessary stages of the development of the technology of fast reactors with sodium coolant been pursued and achieved in the BN type fast reactors.

At present two energy units with fast reactors BN-600 and BN-800 are operating in the Russian nuclear power system. The power unit with BN-600 had been put into operation at the Beloyarsk nuclear power plant in April 1980. In 2010 new license has been granted to operate for 15 years more beyond the design life.

An important step in the strategy of modern Russia for the development of fast reactor technology was putting into commercial operation the newly constructed fast reactor BN-800 (November 1, 2016). The BN-800 will be used to master technology of fast reactors with the use of MOX fuel at an industrial scale and to justify basic elements of a closed NFC.

The next stage of technology development of fast neutron reactors is to justify project of the reactor facility BN-1200. Project materials have shown the possibility of design upgrades, as compared to the BN-800, to improve the safety performance and the achievement of efficiency indicators at the level of today's thermal reactors VVER. This can be achieved by introducing a number of new technical solutions, which are required to be confirmed by relevant R&D. However, for increased competitiveness further optimization of the reactor design and reactor systems is under way.

In addition, the further development of fast reactor technologies is in the BREST fast reactor with lead coolant and dense nitride fuel is currently underway in the framework of "Proryv – break-through" project. Importantly, the BREST technology involves placing the entire infrastructure of the NFC inside the same site with the power unit (on-site deployment of NFC).

The Decree of the Government of the Russian Federation № 1634-r of August 1, 2016 approved the updated scheme of territorial deployment of energy production plants. Under this plan by 2025, nuclear units with BREST-OD-300 reactor will be deployed in Seversk, Tomsk region and leading to the construction by 2030 of 2 nuclear units with BN-1200 reactors at Beloyarsk and South Urals NPPs.

The development of fast reactors cooled by lead-bismuth eutectic in the SVBR-100 reactor is being continued.

Considerable attention in Russia is paid to justification of technologies on a closed NFC. Below are the main achievements have been reached recently in this area:

- On September 11, 2015, the ceremony to pour first concrete for multipurpose fast research reactor MBIR at NIIAR took place; commissioning is scheduled for 2020;
- On September 28, 2015, another ceremony to launch the MOX fuel production at an industrial scale for fast reactors at the site of the MCC took place;
- Launching of the 2nd phase of Experimental Demonstration Center (EDC) for the reprocessing of SNF at MCC of the capacity 250 tons of SNF per year is planned for 2022;
- In 2015, the Russian Research Institutes successfully conducted experiments on separation of Am from Cm for its subsequent transmutation in fast reactors;
- Development of reprocessing technology of fast reactors SNF is conducted in VNIIHT in two directions: hydrometallurgy and pyrochemistry;

- Production Association "MAYAK" started reprocessing VVER-1000 SNF in 2016;
- Experimental assemblies with REMIX fuel have loaded for irradiation in the MIR reactor and in the 3rd unit of Balakovo NPP;

4. Start-up and operation of plutonium-fuelled fast reactors

At the dawn of nuclear power, E. Fermi put forward idea that the first fast reactors will be started up on plutonium that had been produced in thermal reactors.

In Table I, the isotopic compositions of civil plutonium produced in thermal reactors of various types are presented; here also for comparison, the isotopic composition of weapon grade plutonium is presented [7-9].

TABLE I: ISOTOPIC COMPOSITIONS OF CIVIL PLUTONIUM IN IRRADIATED FUEL OF THERMAL REACTORS OF VARIOUS TYPES

Reactor type	Fuel burn-up, GWd/t	Plutonium isotopic composition, %				
		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
PWR	33	1.6	55.5	23.8	12.8	5.4
PWR	60	3.8	51.8	23.0	14.2	7.2
PWR	100	7.8	47.0	21.7	14.7	8.8
MAGNOX	5	~ 0	68.5	25.0	5.3	1.2
CANDU	7.5	~ 0	66.5	26.5	5.5	1.5
Weapon Pu	-	0.012	93.8	5.8	0.35	0.022

As shown by the presented data, there is a considerable amount of the highest even-numbered isotopes of Pu-240 and Pu-242 in civil plutonium, which give a neutron background from spontaneous fission far exceeding that of weapon-grade plutonium. In addition, the rather high content of Pu-238 leads to a considerable decay heat in civil plutonium, and the decay of Pu-241 leads to the high level of radiation.

Fuel based on civil plutonium irradiated in fast reactor will contain the plutonium which isotopic composition essentially in principal does not differ from isotope composition of initial plutonium in fresh fuel.

The isotope composition of the plutonium being continually recycled in a nuclear power system will change with time, reaching in the limit some equilibrium composition. The equilibrium composition of plutonium in a system will be defined by the quantitative ratio of fast and thermal reactors in the system, as well as by conditions of the mixing modes of plutonium produced in the various types of reactors. For fast power reactors it is also possible to introduce the notion of the equilibrium plutonium composition. The equilibrium composition of plutonium is established in a nuclear reactor at large enough number of cycles passing of plutonium through the reactor. The calculations, which have been carried out earlier using a model of fast reactor of the BN-800 type fast reactor, give the results presented in Table II.

TABLE II: EVOLUTION OF PLUTONIUM ISOTOPIC COMPOSITION IN A TYPICAL FAST REACTOR WITH RECYCLES.

Plutonium isotopic composition, % Pu-239/Pu-240/Pu-241/Pu-242		Equilibrium plutonium isotopic composition, % Pu-239/Pu-240/Pu-241/Pu-242
Loading into reactor	Unloading out of reactor	
100/0/0/0	89,2/10,5/0,3/0,02	59,3/31,4/5,7/3,6
60/25/10,9/4,1	58,7/28,4/8,1/4,8	49,1/35,9/7,9/7,1
55/20,8/17,8/5,9	57,5/24,3/11,1/7,1	53,2/33,0/7,3/6,5
43,2/38,8/10,3/7,7	43,8/38,8/9,2/8,2	45,5/37,9/7,9/8,7

Thus, the example once again confirms that fast reactors with plutonium fuel produced in the core discharged plutonium of quite bad quality, thus preventing its ready use in nuclear weapon.

Quite another matter is with fast reactors that have external breeding blankets or internal breeding zones like axial layers inside the core. It is well-known that the blankets produces plutonium with an isotopic composition close to weapon-grade; see for example [9]. It represents a certain risk of proliferation since such plutonium is material belongs to category of direct use materials.

At the export mode of NPPs with fast reactors, it is necessary to have the full and unconditional return of spent fuel to the supplier country. This will require detailed monitoring of the history of fuel irradiation in the reactor, continuous monitoring of SNF presence in storage (wet or dry), and control of returning to the supplier country or to the International Centre for NFC services.

The refusal of blankets eliminates the production of plutonium that would be close to weapons-grade, while, on the other hand, leads to a decrease in breeding ratio and, as a result, leads to the loss of additional plutonium which could be used to speed the expansion of nuclear power.

5. Start-up of fast reactors on enriched uranium

Lately, at least, in Russia, the option is being investigated of the start-up of fast reactors on enriched uranium with the subsequent gradual transition to a mix of U-Pu fuel with the use of its own bred plutonium. Such an option allows fast reactors to be independent of availability of plutonium from the reprocessing of thermal reactor fuel.

At the option both sensitive technologies specified above will be used. Moreover, plutonium with comparably small amounts of the highest mass plutonium isotopes will be formed not only in the blanket but also in the core of the reactor with substantial more amounts.

The isotopic compositions of plutonium which is produced in enriched uranium fuel of the core in BN type and BREST type fast reactors, estimated on the basis of preliminary calculations, are given in Table III [10,11].

TABLE III: ISOTOPIC COMPOSITION OF PLUTONIUM IN SPENT URANIUM FUEL OF FAST REACTORS.

Reactor type	Design fuel campaign, y	Plutonium isotopic composition in spent fuel, %				
		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
BN-1200 with UO2	5	0.4	91.8	7.7	0.3	0.02
BREST-1200 with UN	5	0.1	95.5	4.3	0.1	0.003

It can be shown from the data presented that the contents of Pu-239 and the highest mass isotopes are very close to that for weapon-grade plutonium except for Pu-238 where its content is approximately 10 times higher for the reactor BREST and approximately by 40 times for the BN reactor in comparison with weapon-grade plutonium.

A detailed analysis of the temperature distribution for different models of nuclear explosive devices with the use of civil plutonium has held a famous German scientist Professor H. Kessler [12]. The main conclusion he made based on the results of his studies is as follows: when using an obsolete chemical explosives it is possible to have about 1.8% of Pu-238 in plutonium pit without any tricks for forced cooling. When using modern explosives, Pu-238 content can be up to 3.6% without application of any measures of forced cooling.

6. Possible increase in risk of proliferation in the modern environment

Two “sensitive” technologies developed during the creation of the first nuclear weapons are the most sensitive nuclear power technologies, which is possessed by a limited number of countries. It is reasonable to assume that the increase in the number of countries possessing these technologies increases the risk of proliferation of nuclear weapons (NW).

Despite the accident at the Fukushima-Daiichi NPP in Japan in March 2011, the number of countries declaring their desire to use nuclear energy remains significant, and due to the latest forecast about 15-20 of newcomers will have first NPP by 2030 or some time beyond. The growth of the number of countries and geographic expansion of NPPs forces the discussion about the increasing risk of proliferation, given that the leaders of some countries can obtain or develop sensitive nuclear technologies.

In fact, the development of NW in India and in Pakistan, the continuing tests of NED in North Korea, and the apparent inability of the world community to prevent these actions are examples for other totalitarian regimes on how they might come to possess a NW. Apparently, the NPT needs considerable modernization with enhanced enforcement mechanisms that convince countries that it is unprofitable both politically and economically to obtain or develop a NW. It is perhaps necessary to develop also an international mechanism of compensation to incentivize a nation's disinclination to develop or master the technologies needed to obtain a NW.

For a new country entering into the use of nuclear energy, there will be an important dilemma: namely, to create its own infrastructures of nuclear power, in particular, addressing SNF management, or to use the services provided by one or more of the countries, which have developed such infrastructure. The problem with SNF and the plutonium in it, especially for beginners and the countries with the small nuclear power program is the increased risk of proliferation. This increased risk rises due to possible actions from subnational and terrorist organizations because of the nuclear technologies and materials being subject to inadequate protection in these countries.

7. Features of fast reactors in the field of nonproliferation

It is well known that microscopic cross sections of nuclear materials markedly decreases with neutron spectrum hardening, so the concentration of fissile isotopes in the fast reactor fuel is several times higher than in the thermal reactor fuel. Therefore, nonproliferation of NW and physical protection of NM and NF should be given special or increased attention when it comes to fast reactors and their NFC.

Thermal reactors could not operate without uranium enrichment technology. At long storage times of the SNF of thermal reactors in an open NFC as used today, the risk of proliferation increases over time because of the reduction of the radiation barrier and the possible withdrawal of this fuel by the state-proliferator or its theft by a subnational or terrorist group.

For fast reactors started and operating on a mixed U-Pu fuel, uranium enrichment technology is not required. In a closed NFC, SNF is not supposed to be stored for a long time. With comparatively small technological cooling time after unloading from the reactor this fuel will go directly for reprocessing. Gradual replacement of thermal reactors by fast reactors creates preconditions for the gradual termination of the need for uranium enrichment.

For “gun-type” design of a nuclear explosive device (NED), highly enriched uranium is the most suitable material, the use of civil plutonium is practically impossible. However, we cannot exclude such attempt by a terrorist group.

For an “implosion-type” design, there is a requirement for quite advanced technology, tests of specific components of NED, and operability of the device. It is understood that, for such an advanced device, its development can only be done by a state-proliferator with rather developed technological and industrial infrastructure in the country.

It should be noted here the feature of the fast reactor technology with heavy coolant and operating in on-site NFC. On one hand, the deployment of all nuclear facilities at one site will isolate NM from unauthorized use and will provide comprehensive control to the maximum extent, on the other hand, the export potential of such technology is the subject of system analysis by taking into account all possible factors.

8. The IAEA safeguards

The IAEA safeguards are a set of technical measures for the verification of the political commitment of States in the field of nonproliferation of NW. The IAEA provides safeguards in accordance with its Statute and NPT [13,14].

At the IAEA General Conference in 1965, the first system of safeguards was approved. It comprised detailed procedures for accounting and control of certain NF - originally any power

reactors, and in 1967-1968, this system has been extended to enterprises for SNF reprocessing and for the production of fresh fuel. An important element of the safeguards system is that it provides for unlimited use. In aggregate form, it is known under the symbol INFCIRC/66/Rev.2.
In connection with the NPT entered into force (1968), which established an international legal norm of mandatory application of safeguards in the States - parties to the Treaty, non-nuclear weapons, the IAEA Board of Governors has developed a model agreement on the comprehensive safeguards of the IAEA (INFCIRC/153). The nuclear States - parties to the NPT (USSR, USA, China, UK and France), taking into account the wishes of non-nuclear countries signed an agreement with the IAEA for the voluntary offer of safeguards for their civil NF in 1970-1980.
In order to implement further measures to strengthen the safeguards, which required new legal powers, the IAEA Governing Council in May 1997 approved the Model Additional Protocol (INFCIRC/540) as the standard for additional protocols for more comprehensive safeguards agreements in addition to the INFCIRC/153 document.
The IAEA safeguards are an important element of the global regime of nonproliferation of NW. The safeguards system comprises a number of the following documents that are the basis of safeguards system: the IAEA Statute, contracts and supply agreements requiring the verification of nonproliferation obligations, the basic documents for safeguards, safeguards Agreement and relevant protocols and guidelines relating to the implementation of the IAEA safeguards.
Safeguards in accordance with the IAEA Statute (Art. II), are designed to ensure that NM, services, equipment, NF, and the information provided by the IAEA or at its request or under its supervision or control are not used in such a way as to facilitate any military purpose. The aim of safeguards is to guarantee the timely detection of diversion of significant quantities of NM from peaceful activities to the manufacture of NW or NED. According to the Statute, the IAEA concludes with the State or States agreements, which provide the application of safeguards.

9. Physical protection of nuclear materials and nuclear facilities

Within the IAEA safeguards system, the physical protection of NM and NF is an important element in providing global security. At the International Conference on Security, held 5-9 December 2016 in Vienna, the IAEA Director General Yu. Amano said that terrorists and criminals would use any weakness point in the global system of nuclear security. Any country could be the target of such an attack. That is why effective international cooperation is essential. The overall goal of the state’s physical security system is the protection of persons, property and society (people) and the environment from malicious acts involving NM and other radioactive materials. Recommendations on Physical Protection of NM and NF are set out in the relevant IAEA document [14].
The goals of a system of physical protection of NM and NF should consist in the following:

- Provide protection against unauthorized removal or other unlawful taking of NM;
- Identify the location of missing NM and to ensure the return of the missing NM;
- Ensure the implementation of rapid and comprehensive measures to locate and, where appropriate, to recover missing or stolen NM;
- Ensure the protection of NM and NF from sabotage (diversion).
- Mitigate or minimize the consequences of sabotage (diversion).

It is necessary to ensure that the state’s regime of physical protection should provide the achievement of these goals by:

- Warnings of malicious acts by deterrence and protection of sensitive information;
- Preventing attempts of malicious acts by means of integrated detection system, preventing penetration/moving, and response;
- Mitigating consequences of malicious actions.

It is necessary to ensure that the achievement of the objectives referred above should be carried out in an integrated and coordinated manner, taking into account the various risks for counteracting physical security measures by hostile perpetrators. State’s physical protection regime is intended for all NM: in use, storage and transport, as well as for all NF. State's physical protection regime should regularly review and update, in order to reflect changes in the threats and advances in approaches to physical protection in the field of systems and technologies, and the use of new types of NM and NF.

10. The International Nuclear Fuel Cycle Evaluation

The International Nuclear Fuel Cycle Evaluation (INFCE) was established in October 1977 at the international conference held in Washington, DC [15-17]. Although since then there has been almost 40 years, the main conclusions and recommendations gained during this activity, have not lost their relevance today, especially on nonproliferation in the analysis of fast reactors and NFC. The main reasons for this comprehensive international study of a NFC were as follows:

- Ensuring broad access to nuclear energy used for peaceful purposes to meet the energy needs;
- The need for effective measures to minimize the danger of proliferation of NW, without compromising the development of nuclear power for peaceful purposes;
- The need for special attention to the specific needs of developing countries.

Operation of nuclear reactors will inevitably associated with plutonium production. The problem is not to avoid it, but how to safely deal with this material. Separately danger of diversion of NM at the early stages of the NFC of fast reactors was considered. The experts concluded that this risk does not exceed the danger in the case of uranium-plutonium cycle of light water reactors.

To prevent the use of NM and NF for other purposes, the development of nuclear power must be accompanied by the development and signing of international agreements such as the NPT, the intensification of the IAEA activity to monitor the accomplishment of this treaty - safeguards.

It was noted that the potential of nuclear proliferation of thorium fuel cycle, which uses U-233 with or without Pu, the same as in the case of U-Pu fuel cycle.

It is concluded that measures should be taken to reduce to a minimum the danger of NM diversion without prejudice to the development of nuclear power. Such measures are technical tools, enhanced safeguards system and organizational measures.

The technical measures include measures to reduce the amount of NM in NFC, which is suitable for manufacture of NW, measures for the protection of NM by radiation barrier, and of course, physical security barriers. Deployment of NFC facilities on the same site eliminates transportation of NM outside of the protected area, thereby ensuring the safety of the population, reliable control of NM materials and their physical protection.

During the INFCE studies, no insurmountable problems for the implementation of the safeguards system, relating to existing NF and the NFC, have been revealed. However, in the future, during development of new (NES) it is concluded appropriate to consider the requirements to their designs in order to improve the effectiveness of the measures and to reduce the cost of the safeguards system. This approach also requires the application of safeguards measures at an early stage of NES designing – Safeguards by Design.

The goal of institutional arrangements, as well as technical measures, is to strengthen the protections against the nonproliferation of NW, without stifling the development and accessibility of nuclear power. In the frame of the INFCE proposals for the establishment of international storages of plutonium and SNF, the creation of international and regional centers to provide NFC services and the harmonization of international transport of NM were discussed. An important role in increasing the effectiveness of the safeguards system is given to the growing importance of international coordination and unification of efforts in this direction.

The analysis showed that nuclear power is playing and will play an increasing role in meeting the energy needs of humanity. And in this process fast reactors can play a major role in terms of sustainability that is not evident in most thermal reactor.

With regard to the incentive for the leader of a country to carry out the possession of NW using nuclear power, such a path is not the easiest and least expensive. The INFCE recognizes that comparison proliferation risk, which is inherent in all of the NFC, cannot be carried out separately but depends on many other factors. In addition, there is no NFC completely free from this risk, as well as there is no NFC that are not compatible with the objectives of nonproliferation of NW.

11. Concluding remarks

1. In connection with the large-scale development in Russia of new nuclear power technologies based on the closure of the NFC with fast reactors, Russian experts discuss the possibility of the export potential of these technologies and the impact of such exports to the global nuclear nonproliferation regime. The situation changes significantly if the scope of the export potential in addition to the reactor technologies in the future will involve closed NFC technologies. In terms of compliance with nonproliferation of NW, apparently different approaches to the countries, depending on whether an importer state possesses NW or not, should be developed. An important aspect is also to provide a reliable physical protection of NM and NF, as fast reactors use nuclear fuel with a much higher concentration of fissile isotopes in comparison with thermal reactors.
2. According to the latest forecasts about 15-20 new countries will have their first NPP by 2030. The growing number of such countries and geographic expansion of NPP force discussion about increasing probability of proliferation risk, given that leaders of some countries may seek to acquire or develop sensitive nuclear technologies. For the newcomers there is an important: whether to create its own infrastructure of nuclear power, or use the services of the exporting countries. The underestimation of the problem of SNF, especially for the newcomers, will lead to increase the risk of theft and terrorist acts if inadequate physical protection of NM and NF is implemented in these countries.
3. To start-up fast reactor with plutonium fuel, the use of enrichment technology is not required. Plutonium in closed NFC will be rather poor quality in terms of the use in NW. When for start-up uranium fuel is used then both sensitive technologies have to be used. Moreover, during the first few fuel campaigns plutonium produced in the core will be close to weapons-grade by its isotopic composition.
4. The IAEA safeguards system is an important part of the global regime of nonproliferation of NW. At the present stage of development, the predominant concept is the implementation of the safeguards system in projects as early as possible in the designing of NES. In addition to the IAEA safeguards system, physical protection of NM and NF is an important element of global security, which is the responsibility of the state-owner. In the case of fast reactors, physical protection is to use cutting-edge technological developments and to be a reliable barrier to the theft of NM and terrorist acts.
5. Despite the fact that the INFCE carried out almost 40 years ago, the main conclusions and recommendations obtained in this study have not lost their relevance today, including with regard to fast reactors and closed NFC. It was confirmed that nuclear power is playing and will play an increasing role in meeting the energy needs of humanity. Moreover, in this process fast reactors can play a major role. The INFCE recognizes that a comparative proliferation risk, which is inherent in all of the NFC, cannot be carried out separately; it depends on many other factors, including economy, industry, environment, energy needs, etc. In addition, there is no NFC completely free from this risk, as well as there is no NFC that are not compatible with the objectives of nonproliferation of NW unless carried out covertly.
6. Increasing the export potential of Russian nuclear power technologies at the present stage is possible by including in the country's nuclear power system fast reactors for energy utilization of SNF from VVER reactors. Providing a package of NFC services to foreign partners, especially of newcomers, including the supply of fresh fuel and the return of the SNF for its recycling in fast reactors certainly serves to enhance the export potential of the Russian nuclear power technology and to strengthen the global nonproliferation regime.

7. From the point of view of nuclear, radiological and physical safety and security, any NM carries a certain risk in case if it is handle inadequately from a professional point of view, especially in condition of its unauthorized use. At the same time according to some experts, limited value of enriched uranium below 20% and isotopic composition of civil plutonium are not absolute assurance that NM that satisfies these constraints, cannot be used for improper purposes.

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