ECOLOGICAL FORESIGHT IN THE NUCLEAR POWER OF XXI CENTURY

O. TASHLYKOV[1], S. SHCHEKLEIN[1], Y. NOSOV[2] & O. SMYSHLAEVA[2]
[1]Ural Federal University, Russia.
[2]Beloyarsk NPP, Russia.

ABSTRACT

The access to reliable sources of energy is the key to sustainable development of mankind. The major part of the energy consumed by people is generated with a chemical reaction of fossil fuel burning. This leads to quick depletion of natural resources and progressing environmental pollution. The contribution of the renewable energy sources to the general energy production remains insignificant.

A modern 1,000 MW coal-fired thermal power plant (TPP) burns 2.5 million tons of coal per year and produces significant amount of solid and gaseous waste. TPPs are the largest consumers of atmospheric oxygen and sources of carbon dioxide. A nuclear power plant (NPP) of the same power consumes less than 50 tons of fuel per year. Environmentally significant NPP's waste (liquid, solid and gaseous) is carefully collected, reduced in volume (evaporation, filtering, compaction, incineration, etc.) and securely isolated from the environment at the plant. The annual volume of waste for storage is less than 100 m^3. The waste is under the control of a special NPP's service and regulatory authorities.

The energy of fission reaction millions of times exceeding the energy of burning has an enormous potential that mankind can receive.

Four hundred and thirty-three nuclear power units with a total capacity of about 400 GW exist in the world. The accident at the Fukushima Daiichi NPP in Japan in March 2011 caused anxiety about nuclear safety throughout the world and raised questions about the future of nuclear power. Now, it is clear that the use of nuclear power will continue to grow in the coming decades, although the growth will be slower than was anticipated before the accident. Many countries with existing nuclear power programmes plan to expand them. Many new countries, both developed and developing, plan to introduce nuclear power. Some countries, such as Germany, plan to abandon nuclear energy. The IAEA's latest projections show a steady rise in the number of NPPs in the world in the next 20 years. They project a growth in nuclear power capacity by 23% by 2030 in the low projection and by 100% in the high projection [1,2].

The basis of modern nuclear power comprises water-cooled nuclear reactors which use the energy potential of natural uranium inefficiently (thermal reactors). The thermal reactors use isotope U-235 in which the content of natural uranium is <1%. Breeder reactors are capable of using the significant part of energy potential, which is unavailable to thermal light water reactors. As a result, the same starting quantity of uranium can produce 50 times more energy. These reactors can transform U-238 into fissile Pu-239 in larger amounts than they consume fissile material. This feature is called 'breeding' [3].

The key problem of using the basic benefitsv of nuclear power is to ensure the safety of its use, as well as decommissioning and reliable isolation of process waste from the biosphere. The long-term large-scale nuclear power should possess guaranteed safety, economic stability and competitiveness, absence of the raw material base restrictions for a long period of time and environmental sustainability (low waste). The nuclear power systems with fast neutron reactors and liquid metal coolant can satisfy these conditions.

More than 40 years of Russian experience in the field of construction and operation of sodium fast reactors makes it possible to summarize and analyze the ecological features of reactors of this type, the possibility of their use for sustainable energy supply of mankind and solving environmental problems.

Keywords: closed nuclear fuel cycle, collective dose, fast breeder reactor, nuclear energy systems, nuclear power plant, safety.

ISSN: 2056-3272 (paper format), ISSN: 2056-3280 (online), http://www.witpress.com/journals
DOI: 10.2495/EQ-V1-N2-133–140

1 THE MAIN REQUIREMENTS TO THE ADVANCED NUCLEAR POWER

The growth of the global energy consumption due to population growth and rising living standards leads to shortages of fossil fuel resources. There are some concerns about volatile fossil fuel prices and security of energy supply. The increasing use of fossil fuels leads to growth of pollutant emissions, including greenhouse gases.

The sustainable economic development in the world is largely determined by the availability of energy resources. If the share of costs for the primary energy sources in the gross domestic product in the world economy exceeds the critical level (10%), it leads to global economic crises [4], for example in 1980 and 2008.

From the authors' point of view, to solve this problem, it is necessary to increase the use of renewable and nuclear energy. The unique feature of nuclear power is nuclear fuel breeding. This determines the prospects for its use. Currently, this feature is underused as uranium resources are available.

Modern nuclear power using thermal reactors suffers systemic problems, which include a continuous increase of the amount of spent nuclear fuel (SNF) and radioactive waste (RW) (a near-term problem), and limited fuel base due to low efficiency (<1%) of natural uranium use (a long-term problem).

There are two main options for SNF: a once-through cycle in which fuel is used only once and then stored as waste and a re-use cycle in which SNF is recycled with uranium and plutonium extraction for their final burning in reactors.

In recent years, international cooperation in developing generation four nuclear energy systems is actively carried out. The term 'nuclear energy system' includes a reactor and reprocessing (recycling) of nuclear fuel. Compared with the previous generations, the new system should have better performance in the field of sustainable development, competitiveness, safety and reliability, as well as proliferation resistance.

Observation of the highest nuclear safety standards is a precondition for large-scale development of nuclear power in the 21st century. An important feature of a nuclear power plant (NPP) safety is the limitation of its possible impact on the population in case of accidents. As far as safety requirements are getting more stringent, the dimensions of the zone of possible population evacuation are minimized. For the new generation of NPPs, the task is set to eliminate completely the need for evacuation of the population from the plant location area in case of any technically possible accident.

The list of the proposed generation four nuclear power systems includes a system with a sodium fast neutron reactor and a closed nuclear fuel cycle (NFC) providing an effective treatment of actinides and fissile material breeding.

2 METHODS AND TECHNIQUES

2.1 The justification of the selection of a sodium fast reactor for an advanced nuclear power system

Fast reactor NPPs are an advanced type of NPPs and have the following main advantages [5]:

- Possibility to work with low (close to atmospheric) pressure in the reactor vessel, which radically decreases the risks of radioactivity escape.
- High thermal effectiveness and reliability of the reactor circuit equipment operation (complete absence of corrosion and deposits on the surfaces of fuel elements and heat exchanging equipment).

- Possibility to obtain high temperatures of coolant, which increases the NPP's thermodynamic effectiveness and offers the challenge of creating nuclear engineering complexes for non-ferrous metal industry and chemical industry.
- Minimal initial reactivity margin, which practically excludes a possibility of nuclear-hazardous events.
- Minimal volume of the process waste (10–20 cubic meters per year).
- The lowest among all NPPs level of personnel radiation load (10 up to 100 times less) and complete absence of bioenvironmental effect.
- The most efficient among all NPP types use of nuclear fuel (the burnup is 2–2.5 times higher than at traditional reactor systems).
- Possibility of expanded nuclear fuel production (breeding).
- Sodium reactors have additional inherent self-proofed features increasing their safety:
- Sodium effectively retains isotopes of iodine and cesium (which is confirmed by the operating experience from BN600), which eliminates the release of the dangerous isotopes of the gas–aerosol fraction of the fission products into the environment during normal operation and accidents.
- Weak corrosion-erosive effect of sodium on the structural materials eliminates the risk of overheating the fuel rods both due to the clogging of the flow cross section of the fuel subassemblies (S/A) and loss of integrity of the reactor vessel.
- Good thermal and physical properties of sodium increase the efficiency of heat removal and dissipation in emergency situations.

Russia has a significant scientific, technical and engineering backlog in the field of fast neutron reactors and experience in their technological use (desalination and central heating). Beloyarsk NPP unit No. 3 with BN600 fast neutron reactor of the rated electrical output of 600 MW has been in operation since 1980. This is the only commercial fast reactor successfully operating for a such a long time. During this period, the technology of safe handling of sodium was mastered and improved. The design service lifetime of the unit was scheduled until 2010. On the basis of the accumulated operating experience, the evaluation of the condition of the materials and upgrade and replacement of some equipment were done to obtain the license to operate it until 2020 with the right of further extension [6].

In June 2014, BN800 reactor (BNPP unit No. 4) designed on the basis of BN600 reactor and having improved engineering-and-economical and safety performance obtained its first criticality. BN800 design foresees additional passive-type reactor emergency protection. The reactor decay heat removal system using air-to-air heat exchangers has been implemented. The corium trap to localize the melted parts of the core in case of a postulated accident with failure of all reactor protection systems has been foreseen. BN800 is a necessary step in creation of a new commercial fast reactor. The reactor is supposed to use MOX-fuel (mixed oxide fuel is nuclear fuel that contains more than one oxide of fissile material, usually consisting of plutonium blended with natural uranium, reprocessed uranium or depleted uranium) for the utilization of weapon-grade plutonium with the MOX-fuel burnup being up to 15% of h.a. and more, to tests high-density fuel types with the breeding ratio at the level of 1.35, …, 1.45, to optimize the closed fuel cycle technology with MOX-fuel and also to organize burning of minor actinides accumulated both in this reactor and in thermal reactors. The designed lifetime has been increased from 30 years (BN600) up to 45 years with the prospect of its extension up to 60 years. Nowadays, BN1200 reactor is being designed in such a way that it can be used in a generation four nuclear power system with a closed fuel cycle. The concept of the future BN1200 power unit is based on the significant positive experience of Russia in the development and operation of sodium fast reactors and the maximum possible use of the achievements of this technology. BN1200 design relates to reactors with enhanced safety due to the optimal combination of the reference and new solutions, assurance of high safety indicators and engineering-and-economic performance, the possibility of nuclear fuel breeding. The probability of severe core damage for BN1200 is one order less than that is required in the regulatory documents. The control area is within the site boundaries for any design basis accident [5]. BN1200 design envisages the increased level of radiation and fire safety. All the systems with radioactive sodium are located within the reactor vessel, which excludes the possibility of radioactive sodium release into the reactor premises and the external communications. The decreased power density of the core and prolonged storage of the spent fuel sub-assemblies (SFS) in the in-vessel storage for up to 2 years will three times reduce the specific power density of the fuel. This increases the safety of transportation and sodium washing of the SFS before they are installed in the spent fuel pond.

The length of the secondary sodium pipelines is reduced almost three times as compared with BN800 ones due to transition to a shell-type steam generator and application of bellows expansion joints. All the pipelines will have guard covers. This eliminates large leaks and fires of non-radioactive sodium.

2.2 Analysis of a fast NPP influence on the environment and personnel

For more than 30 years, Beloyarsk NPP (BNPP) has been operating reliably and safely the world's most powerful BN600 fast breeder reactor. As the long-term operating experience shows, BN600 is one of the most environment-friendly reactors.

The main types of non-radiological impact on the environment of Beloyarsk NPP are as follows: thermal impact, discharge of pollutants into water bodies, polluting emissions into the atmosphere and on-site waste storage.

The thermal efficiency of fast reactor NPPs is more than 40%, which significantly decreases heat emissions to the environment in comparison with traditional NPPs with 'thermal' reactors (thermal efficiency: 31–33%).

According to the State Report, 'On the condition of the environment and impact of the human environment factors on the health of general public in Sverdlovsk region', BNPP's contribution to the gross amount of the atmospheric and liquid discharges is at the level of the basis point. Meanwhile, the main sources of discharges (more than 98% of all NPPS' sources) are boiler-house plants fired with fuel oil.

The emissions of the radioactive substances into the atmosphere from Beloyarsk NPP are mainly accounted for by the inert radioactive gases (IRG) and, as a rule, amount to <1% percent of the permissible value (Fig. 1) [5].

The systematic measurements of the concentration of radioactive substances in atmospheric air and cooling reservoirs, as well as the measurements of the activity of the soil and vegetation and that of the food at the monitoring points confirm the insignificance of the influence of the NPP performance during normal operation on the state of the objects in the environment. At the same time, the radiation risk for the general public living in the vicinity of Beloyarsk NPP is within the range of the unconditionally acceptable risk, which does not require any additional measures to be taken to reduce the activity of radionuclides in the atmospheric and liquid discharges from NPPs.

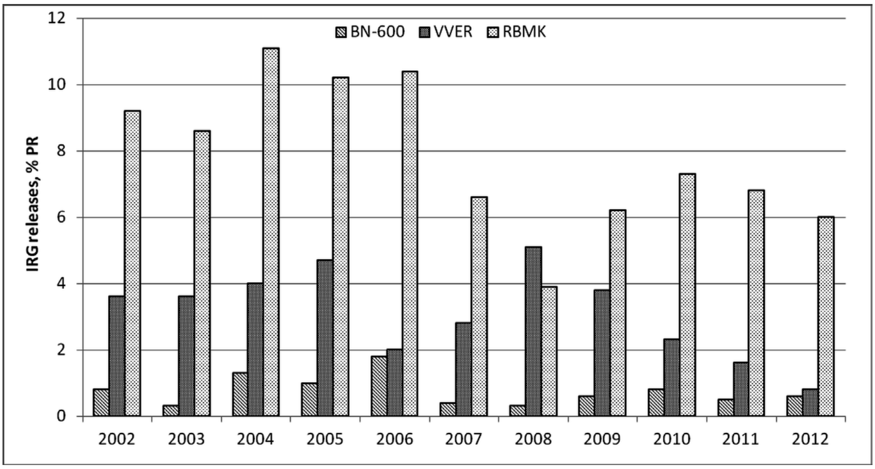

Figure 1: The release of the inert radioactive gases from different NPP types (% of the permissible release).

The complex of the ‘dry’ waste storage is located within the NPP territory inside the guarded perimeter and is designed for storage of solid radioactive waste (SRW). The storages correspond to the standing regulations for the long-term bulk storage of the non-conditioned SRW. The technical condition of the liquid waste storage equipment corresponds to the design specifications and meets the requirements of the operational documentation.

The radiation monitoring of the objects in the environment within the control area and surveillance area is conducted by the off-site radiation monitoring group, which is a part of BNPP’s Radiation safety department. In addition, the monitoring of the state of environment is conducted on the basis of the results of the long-term observation. The trends in the parameters of the monitored objects are followed.

The automated radiation monitoring system is designed for the continuous measurement of gamma radiation dose rates and temperatures at the specified points of the site, control area and surveillance area of Beloyarsk NPP. The measurement results are transmitted via the radio channel to the Crisis Centre of JSC ‘Concern Rosenergoatom’ and ‘Rosatom’ Corporation’s Crisis Management Centre.

For BN600 reactor power unit, some of the lowest dose levels both in Russia and in the world were achieved (Figs 2 and 3). At the same time, the repairs account for 50–75% of the collective dose [7].

The total exposure caused by the work on the lifetime extension for the period of 2005–2010 is much lower for the RBMK and VVER-type reactors [5]. This is largely contributed by the pool arrangement of BN600 reactor with the main primary components enclosed in the reactor vessel. The decrease of the collective doses in 2012 was due to completion of the activities related to unit No. 3 lifetime extension.

3 RESULTS AND DISCUSSION

The NFC based on fast reactors (Fig. 4) makes it possible to minimize the volume of RW and optimize the use of natural resources. Transmutation of transuranic elements is most effective

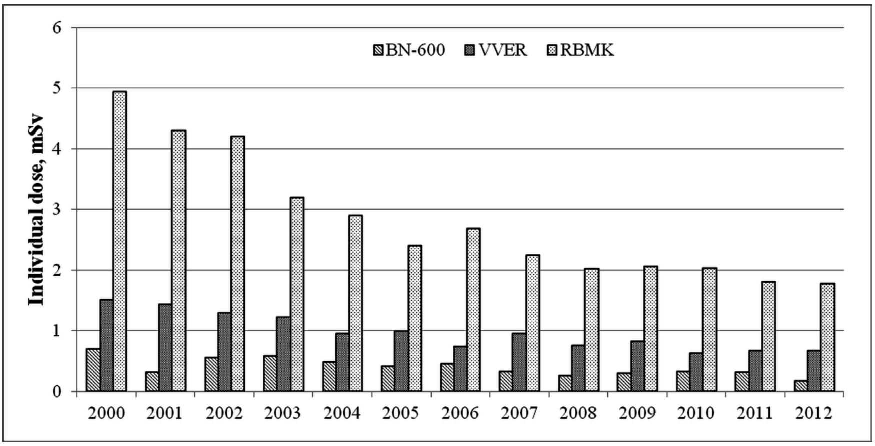

Figure 2: Weighted average individual exposure doses to personnel at Russian NPPs by reactor types.

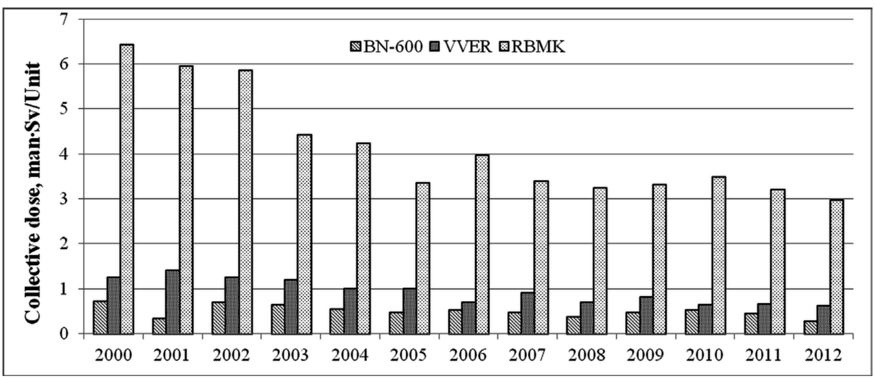

Figure 3: Collective exposure doses at Russian RBMK, VVER and BN600 reactor nuclear power plant units.

in fast reactors. Most transuranic elements exhibit fissionability with neutrons of the fast spectrum with energy release. Therefore, a less amount of them will pass into the high-level waste.

The results of the NFC closing analysis show that the systemic problems of the existing nuclear power (continuously increasing amount of SNF and RW and inefficient use of natural uranium) are solved by forming a nuclear energy system, which consists of fast reactors with improved fuel breeding parameters combined with VVER-type reactors if fuel reprocessing and recycling are assured. Creation of a serial unit with BN1200 sodium fast reactor of high power suitable for commercial operation is one of the strategic priorities of the Russian nuclear industry. It promotes the transition to a new technological platform – a closed NFC on an industrial scale.

The serial BN1200 power unit working in a closed NFC will extend manifold nuclear power fuel base due to the involvement in the production cycle of uranium-238 isotope unused today. It will also help to minimize the formation of RW and dispose the most problematic elements of the radioactive spent fuel from other reactors. Combined operation of serial fast reactors and thermal neutron reactors will bring the nuclear power to a qualitatively new level of development, making it possible to use the most advanced technology of energy production and the maximum achievable ecological cleanness of the entire process, from uranium mining to waste disposal.

The sodium reactor technology is regarded in Russia as a priority for the following reasons:

- In the short and medium terms, there is no alternative to the introduction into a closed NFC of a different reactor technology but the technology of sodium fast reactors obtaining the necessary validity, engineering-and-economic characteristics, the reference and operating experience.
- In a closed NFC, this technology provides for disposal in fast neutron reactors of plutonium reprocessed from the spent fuel of VVER-type reactors (and both VVER and BN-type reactors use MOX fuel).
- It is possible to replace the construction of VVER power units with BN1200 ones in the investment programme of the State Corporation 'Rosatom', provided that the costs of their construction and operation will exceed the ones of the VVER technology by not more than by 15% which has been estimated to be achievable [4].

The architecture of the future nuclear energy systems satisfying the requirements of stability and safety includes fast reactors with nuclear fuel breeding combined with thermal reactors. In this case reprocessing, multiple recycling of fuel, separation and isolation of RW will provide unlimited resources of nuclear fuel due to production of ^{239}Pu and ^{233}U from natural uranium and thorium, reduce the volumes of SNF storage facilities and solve the problem of RW treatment.

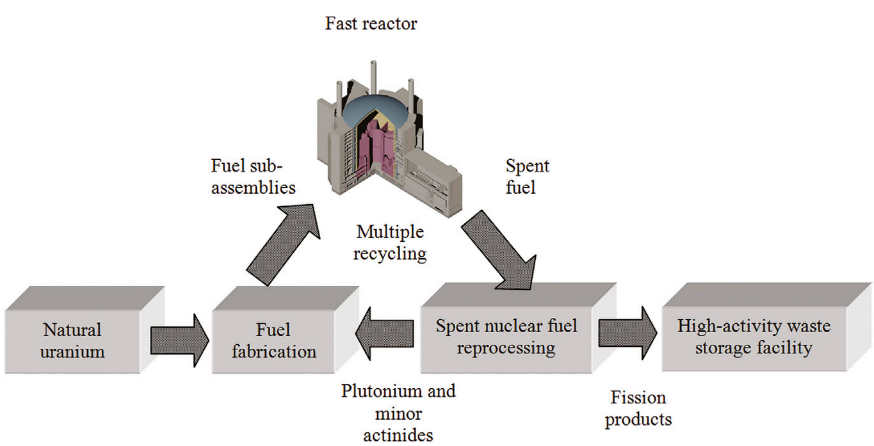

Figure 4: Fast reactor based fuel cycle.

4 CONCLUSIONS

1. In the foreseeable future, it is impossible to provide sustainable energy supply in the world without the use of nuclear power.
2. The developing innovative nuclear energy system with sodium fast reactors and a closed NFC meets the principles of sustainable development and contributes to solve the problems of energy supply security.
3. The accumulated experience in the design, manufacture and operation of fast neutron reactors indicates that the technology in Russia is practically mastered, and the degree of its reliability and safety meets the requirements to an advanced nuclear technology.

REFERENCES

[1] Amano, Y., Nuclear power in the 21st century, https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull54-1/54104710202.pdf

[2] Bychkov, A., Nuclear power today and tomorrow, https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull54-1/54104710707.pdf

[3] http://www.atomic-energy.ru/technology/34307

[4] Ponomarev-Stepnoy, N.N., Zrodnikov, A.V. & Koltun, O.V., Perspectives of development and implementation of closed fuel cycle. *Proc. of the 9th International Scientific Technical Conference 'Safety, Efficiency and Economics of Nuclear Power Engineering'*, Rosenergoatom: Moscow, pp. 19–22, 2014.

[5] Tashlykov, O., Shcheklein, S., Sesekin, A., Chentsov, A., Nosov, Y. & Smyshlaeva, O., Ecological features of fast reactor nuclear power plants (NPPs) at all stages of their life cycle. *1st International Conference on Energy Production and Management in the 21st Century: The Quest for Sustainable Energy*; Russian Federation: Ekateringburg; 23–25 April 2014 . *WIT Transactions on Ecology and the Environment*, **190**, pp. 907–918, 2014.

[6] Nosov, Y.V., Smyshlaeva, O.Y., Tashlykov, O.L. & Shcheklein, S.Y., Ensuring of ecological safety over a long period of exploitation of the fast breeder reactor on the example of Beloyarskaya NPP. *Alternative Energy and Ecology*, **4(108)**, pp. 64–68, 2012.

[7] Tashlykov, O.L., Shcheklein, S.E., Bulatov, V.I. & Shastin, A.G., Problem of the lowering of the nuclear power plant personnel exposure. *Communications of Higher Schools, Nuclear Power Engineering,* **1**, pp. 55–60, 2011.