EVOLUTION OF THE TECHNICAL CONCEPT OF FAST REACTORS: THE CONCEPT OF BREST

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Abstract

A new reactor concept BREST, which will adequately meet the variety of cost-efficiencies and safety requirements set for power industry demand within contemporary understandings, has been developed based on the lessons learned from a 50-year experience in the fast reactor development in Russia. The BREST reactor concept adopts most features of the IFR concept. However, several advances in consistent implementation of natural safety principle and in increase of unit power without sacrifice due to its reduction have been achieved in the BREST reactor design. Applications of the high dense and heat-conductive mono-nitride fuel, and the lead-bismuth coolant having high degree of natural circulation are incorporated to facilitate the long-lived high-level radwaste treatment and the natural safety principles in the BREST reactor design. The 40-year experience gained in the lead-bismuth cooled submarine development and the results obtained from core physics experiments and lead coolant experimental works allowed to begin detailed design of a demonstration power unit consisting of BREST-300 reactor and on-site fuel cycle facilities. The construction of the BREST-300 power unit is scheduled for its completion in the first decade of the 21st century. A feasibility study for two BREST-1200 power units demonstrated its superior economics to LWRs of the same power output. Several calculational and experimental works, and design efforts for clarifying the applicability of developed lead-bismuth coolant technology to the lead coolant are under way. An international cooperation on those efforts would substantially contribute to the BREST reactor development.

1. TECHNICAL CONCEPTS OF FAST REACTORS

In the course of nuclear weapons development in the USA and the USSR in 1940s E. Fermi, A. Leipunsky and other nuclear physicists had evaluated a unique surplus of neutrons in the fast U-Pu reactors. If calculated per a burned Pu nucleus excluding 1 neutron for continuation of the chain reaction, about 2 neutrons are left available as compared with the thermal reactors, viz. 1 neutron in case of ^{235}U or Pu and ~ 1.2 for the Th-^{233}U cycle.

It allows with a high degree of confidence to reach breeding ratio BR $\geq$ 1, enhance by two orders of magnitude the degree of uranium utilization and involve uranium from low-grade ore in the fuel balance. As a result, nuclear fuel resources will increase dozens of thousands or, perhaps, millions times, so we can justifiably consider them drainless.[1]

At the same time, the surplus of neutrons is the most important prerequisite for resolution of other global challenges of nuclear power formulated by E. Fermi as back as 1944: safety and dependent cost–efficiency of the reactors, radwaste, non–proliferation.

Having understood that conventional power was limited by available fuel resources (as well as the environmental concern, as we should add at present) and willing to use the advantages of defense nuclear power achievements, the outstanding physicists initiated development of civil nuclear power which would be capable to replace "chemical" power industry.

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[1] Water in the world oceans contains ~ 4×10^9 t of dissolved uranium salts which can be extracted at the cost greater by only one order of magnitude than the current costs, as estimated by Japanese specialists. For the fast reactors it is quite acceptable. Total uranium resources in the earth crust amount to ~10^{14} t, or average concentration of ~ 10^{-6}. The appreciable portion of the resources can be accepted as fuel for the fast reactors.

In 1952 the first pilot fast reactor EBR–I was commissioned in the United States of America to generate electricity by means of a nuclear source.

The successful experience with the BR–5 reactor with oxide fuel and Na (1959, USSR) paved the way for development of the first nuclear power plants (NPPs) with similar reactors in the USSR, France and the UK in 1970s – 1980s.

The experience of thermal reactors on the basis of ^{235}U fuel designed in 1940s in the USA and the USSR for production of weapons–grade Pu and U (graphite, heavy–water reactors) and in 1950s for nuclear submarines (light water reactors) can also be used in nuclear power. As long as inexpensive uranium with its concentration in the ore $\geq 10^{-3}$ is still available (potential resources are estimated as 10^7 t), the cost of fuel for thermal reactors will not be high, and such NPPs can successfully compete with conventional power plants (fossil, oil and gas), provided that their construction is rather inexpensive. These arguments set the basis for the first stage of nuclear power development in 1950s with the use of above–mentioned reactors (the first NPP was commissioned in the USSR in 1954).

However, since less than one percent of uranium can be utilized in thermal reactors, the cheap resources of uranium proved to be in a shorter supply than oil and gas resources, to say nothing about coal resources. For this reason a large contribution of nuclear fuel to the world nuclear power cannot be expected. Indeed, after the peak 16% (6% in the fuel balance) and a much higher share in some countries where fuel is scarce, the uranium contribution will be decreasing in the future decades according to the estimations.

Scarce supply of cheap uranium had been a matter of concern from the very beginning of nuclear power development, but Pu produced in the thermal reactors ($\sim 10^4$ t Pu per 10^7 t of consumed U) was supposed to be used as fuel for the fast reactors which would not be limited by fuel resources. After the World War II nuclear power was growing at the record pace and many scientists believed that civil nuclear power riding along the success in defense area could constitute thousands GWs by the end of this century.

To attain this goal, the fast reactors should be designed to provide high rate of Pu breeding, i.e. high breeding ratio (BR) and high fuel power density. Therefore, the following design solutions were selected for the first generation: light heat–conductive Na, U blanket that could make up for a decrease in BR when oxide fuel was applied because of its well–known characteristics to facilitate designing. Dense and heat–conductive metal U–Pu alloys, monocarbide and mononitride fuel were put under R&D activities for the future applications, as these fuels were preferable for fast reactors along with “dry” fuel reprocessing technology, as opposed to water–chemistry techniques for production of weapons–grade Pu.

The events that took place in 1970s and 1980s had changed drastically the situation in power industry, and particularly in nuclear power. Anticipated rates and scales of nuclear power development turned to be unprepared and unclaimed due to the following:

- Oil crisis in 1970s had been mitigated by means of energy–saving measures and stabilization of the fuel market. Rate of power industry progress in developed countries was slowing down;
- The increased rate of the natural gas production. Implementation of gas turbines for the purposes of power industry and resulting rise of its cost–efficiency;
- Accidents at the nuclear power plants, concern over radwaste disposal, anti–nuke movement. NPP safety had been improved but at the expense of higher cost of electricity

generated at NPP;

- Fast reactors proved to be the most expensive. Higher risk of nuclear weapons proliferation in case of closed nuclear fuel cycle.

A swell in nuclear power development in 1960s and 1970s was followed by stagnation. Construction and even designing of fast reactors have been phased down at first in the USA and now in Europe. To dispose accumulated spent fuel and Pu, the closed LWR fuel cycle and various burners were developed, though being uneconomic measures. As a result, the large–scale development of nuclear power on the basis of fast reactors could be significantly reduced or even eliminated at all.

The interest in nuclear power and fast reactors is kept up by Asian countries striving for industrial development and lower dependence on fuel suppliers. However, as yet these countries just follow the way went by the USA, Russia and Europe in this century.

Meanwhile, according to the estimations, population will double and the world demand for energy will rise three times, mainly owing to the needs of developing countries, in the coming century. These trends would probably involve the global risk of depleting the cheap resources of organic fuel, destabilization of the fuel markets and getting to hazardous limits on combustion products release, especially if more coal would be burned.

Stabilization of chemical fuel consumption will require advanced power technologies capable to provide large–scale replacement of fuel. Fast reactors are believed to be the most realistic and efficient solution, provided that some specific concerns associated with fast reactors will be resolved.

The designs of EFR and BN–800 (the latter's NPP construction on the site of Beloyarsk has already started) demonstrate the capabilities of evolutionary development of a traditional concept of fast reactor design, cost reduction being one of them.

Nevertheless, the lessons learned from a 50–year experience and new conditions set for power industry demand for development of a new concept for fast reactor which will adequately meet the variety of cost–efficiency and safety requirements in their present–day understanding.

2. NEW EVOLUTIONARY CONCEPTS

The TMI and Chernobyl accidents revealed not only defective design and operation procedures applied at the nuclear power plants, but also inadequacy in the philosophy of safety as it was developed on the basis of overall–positive, though limited, experience obtained at the defense nuclear reactors and first civil NPPs. The safety concept allowed large margins for reactivity effects and chemically active coolants that boil at low temperature and might lead to reactor runaway accidents, loss of cooling capability, fire, steam and hydrogen explosions. These hazards can be mitigated at the expense of heavy–duty engineered systems and barriers, tightening of the requirements to equipment and personnel. Though severe accidents could not be completely eliminated, these safety measures reduce probability of such accidents along with higher cost of NPP. PSA methods allow to predict at a certain degree of confidence the safety of nuclear power plants, as long as the evaluations are kept close to the accumulated experience of 10^4 reactor–years. However, similar predictions for large–scale nuclear power which would operate during ~ 10^6 reactor–years cannot be based on neither experimental data, nor convincing theoretical justification.

The term “inherent safety” coined by A. Veinberg and introduced in common use after the TMI accident could be regarded as a key principle of a new nuclear power philosophy that includes the economic concerns as well, since the main expenses for nuclear energy go for provisions of NPP safety. It seems reasonable to apply this philosophy to the whole fuel cycle, including radwaste and non–proliferation problems which are not clearly categorized as yet.

The Russian synonym “natural safety” is believed for us to be a proper term for this extended conception. A natural safety approach to the nuclear reactors means, first of all, the rejection of potentially dangerous design solutions for attaining safety and their replacement with rather reliable, as opposed to engineered measures, physical and chemical properties and relationships inherent for fuel, coolant and other components. So when A. Veinberg claimed for deterministic safety rather than scholastic absolutes, he meant reduction of the occurrence probability of severe accidents associated with a catastrophic release of radioactivity to evidently negligible values. Low reactivity margins and effects, the use of chemically inert coolant that boils at high temperature and other measures make it possible to exclude fuel damage under any human errors, failures of components and even external impacts, except for extreme nuclear or other impacts leading to a complete NPP destruction. Other beneficial factors are as follows: efficient feedback, high degree of natural circulation of coolant and air for the purposes of decay heat removal.

For the reason of neutron surplus, fast reactors can use fuel with a balanced composition ($Pu : {}^{238}U \sim 0.1$, $CBR \cong 1$). Only dense fuels conform to this requirement which is the most important factor of inherent safety, as it allows to reduce a total reactivity margin under high heat conductivity of fuel to $\Delta k_{tot} \leq \beta_{eff}$ as compared to dozens of β_{eff} for modern reactors. Many other advantages can also be obtained.

The balanced composition of fuel also permits to refuse the extraction of Pu during fuel reprocessing. In combination with rejection of enriched uranium, the transfer to fast reactors will eliminate the major factors of risk associated with nuclear weapons proliferation as nuclear power spreads all over the world. Realization of the international non–proliferation regime can be facilitated and reduced to supervision over possible set-up of illegal Pu extraction and U enrichment facilities. Fuel reprocessing technology can also be facilitated.

Neutron surplus in fast reactors is beneficial in other respects as well. In particular, radwaste management problem can be resolved in line with natural safety principles by means of transmutation of all actinides into fission products (FPs) and long–lived FPs (${}^{129}I$, ${}^{99}Tc$, etc.) into short-lived and stable nuclides. Radwaste decontamination from actinides to the factor of $\sim 10^{-3}$ would provide the balance between radioactivity of disposed radwaste and uranium taken from mines.

3. BREST REACTOR DESIGN DEVELOPMENT

Development of a new concept of fast reactor design had been started in Russia in 1970s after the commissioning of the BN–350 reactor and the completion of BN–600 design with a view to resolve revealed challenges. The Chernobyl accident and other events in nuclear power gave a stronger impulse to this work. From the beginning of 1990s, thanks to the support provided by Ministry for Atomic Energy, Ministry of Science and Russian Academy of Sciences, these activities have been performed in a more consistent and planned way.

The work was much influenced by the concept of IFR developed in ANL, USA. Many provisions of this concept were applied to our design, including the use of dense fuel, on–site fuel cycle facilities with dry fuel reprocessing and some others. At the same time, we believe that Na cooling and metal fuel could not properly meet the natural safety principles, whereas the advantages of a modular design (PRISM) do not compensate the economic losses because of decreased unit power and make it more difficult to use fuel with balanced composition.

According to preset goals, BREST reactors should be designed such as to implement consistently the principles of natural safety without a sufficient deviation from the materials and technology which had been proved in defense and civil nuclear power facilities. On the other hand, advanced, though not yet completely justified design solutions should not be sacrificed for the sake of quick construction, as happened with the previous designs of fast reactors, which is why their huge potentialities could not be implemented fully.

Slowdown of the power growth rate in the world (estimated for the next century as just a little over 2% per year, i.e. triplication of installed capacity for 50 years) and accumulation of up to $\sim 10^4$ t of fissile Pu produced in thermal nuclear reactors allow to neglect the need for a short doubling period and a basic requirement for excessive Pu production. As a result, the highest level of safety and cost–efficiency became the top priority.

Lower fuel power density makes it possible to transfer from Na to heavy, low–activated, chemically inert lead (Pb) coolant that is characterized by low absorption and neutron moderation capabilities. In terms of its physical and chemical properties, except for the melting temperature, Pb is similar to lead–bismuth (Pb–Bi) coolant which has been used for 40 years in the nuclear reactors for Russian submarines.

There are some concerns regarding applicability of the corrosion–resistant technology developed for Pb–Bi coolant to Pb coolant. Another problem is avoidance of cold water ingress to steam generators that may lead to Pb freezing. Design efforts, calculations and experimental works are underway to clarify and eliminate the problems mentioned above.

The high dense and high heat–conductive mononitride fuel with balanced composition, tested in the BR–5 reactor and the loop experiments, has been selected. This year it is planned to install a loop channel with Pb and BREST fuel into the BOR–60 reactor.

A series of physical experiments with Pu–U–Pb core have been conducted and some of them are underway at the BFS critical assembly.

The obtained results allow to begin detailed design of a demonstration power unit with the BREST–300 reactor and on–site fuel cycle facilities with dry fuel reprocessing technology. The first stage of detailed NPP design as applicable to the site of Beloyarsk has been completed. Designing and construction of the power unit are scheduled for completion within the first decade of the 21th century.

A feasibility study has been performed for the NPP with two BREST–1200 units. The study demonstrated that the cost of NPP with an inherently safe fast reactor would be significantly lower than the cost of NPP with LWR of the same power output.

The investigations and developments performed so far let us hope that demonstration of the fast reactor and fuel cycle of natural safety will open up the optimistic prospects for a new stage of nuclear power capable to find the answers to the urgent fuel and energy problems. Participation of other countries interested in nuclear power production can substantially contribute to the success of this project.