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Challenging Scientific and Technical Problems of Nuclear Power

Yu. A. Olenin[a,*] and V. I. Il'gisonis[a,,#]**
[a]*Rosatom State Atomic Energy Corporation, Moscow, Russia*
**e-mail: YuAOlenin@rosatom.ru*
***e-mail: VIIlgisonis@rosatom.ru*
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Abstract—The current problems and prospects of Russian nuclear power are discussed in this work based on the material of the report presented at the scientific session of the General Meeting of Members of the RAS on November 13, 2018. The conclusion is made that the nuclear industry could be a powerful driver of scientific and technological progress, a mechanism stimulating the development of a wide range of industrial and technological segments of the national economy.

Keywords: nuclear power, nuclear reactor, nuclear fuel cycle, fast neutron reactor, radioactive waste, spent nuclear fuel, molten salt reactor, small nuclear power plants, hydrogen energy, thermonuclear fusion.

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Today the intrigue of the Russian nuclear industry is the appearance of new tendencies in the development of world energy, primarily, electrical energy, that make us rethink of typical predictions of linear growth in installed capacities of nuclear power plants, which have been known since the middle of the twentieth century. These tendencies are based on both objective factors and an interpretation that, however, cannot always be considered appropriate.

First, in recent years, the annual generation of electrical energy has changed the dynamics of volume growth, which is steadily recorded throughout the entire history of the development of the electrical energy industry [1]. In the early 1990s, this process was hastened (i.e., the second derivative was positive), but today electrical energy is consumed at decreasing growth rates, which means that we cannot expect that electrical energy generation will grow too high in the near future, especially if we mean a few decades, which is the scale of nuclear power operation.

Second, the forced development of energy-saving technologies related especially to renewable energy sources creates a sense of no need to create new energy sources and that the available capacities are sufficient.

Third, in thinking of the basic competitive advantage of renewable energy sources, ecological safety and the rate of development of these resources, a conclusion is often made that nuclear power can be forced out from the world energy pattern without serious consequences.

We recall that currently nuclear power has a share of about 10% in the global generation of electrical energy and almost 19% in production by our country. In the European part of Russia, about 40% of electrical energy production is accounted for by nuclear power plants. It is also important that today's construction, renovation, and reconstruction of nuclear power plants abroad are one of the most dynamically developing items of nonresource high-technology export of our country. In terms of volume, it is comparable with the arms export: Rosatom has already concluded contracts for the construction of 36 blocks abroad totaling more than $130 bln in the coming decade.

The question is if there is any reason to count on the further development of nuclear power and to offer it as a promising component of the Russian economy in view of all the tendencies mentioned.

First of all, we should remember that the forecasts for global energy consumption may change completely just in the next decade. The reasons are the scaled electrification of transportation, the processes of digitization, which have progressed not only in Russia, but also abroad and are rather expensive in terms of energy consumption. In particular, in the European Union they are among the priority areas of scientific and technical progress. Finally, the uneven development of the regions in the world indicates that the electrical energy industry has enormous potential: about one

[#] Yurii Aleksandrovich Olenin, Dr. Sci. (Eng.), is Deputy Director General for Science and Strategy of the Rosatom State Corp. Viktor Igorevich Il'gisonis, Dr. Sci. (Phys.–Math.), an R&D Line Director of the Rosatom State Corp.

billion people today are not provided with electrical energy. We note that more than a three-time growth of production and consumption of electrical energy over the past 20 years has placed the Asian region among the global leaders. Thus, if we focus on the possible changing tendencies in electrical energy consumption, we will have to accept the need of a new generation for electrical energy for the global economy, and nuclear power can play a significant part.

Special comment should be made about profitable investments in nuclear power, since the construction of a nuclear power plant is certainly an expensive business with a return over decades. In terms of economics, if we use a Levelized Cost of Energy (LCOE), which includes all costs from the construction of a facility to putting it out of operation, we see that today as a result of mass adoption of renewable energy sources, LCOE for them has already been at the level of the other sources of generation or even below. Nevertheless, we should bear in mind the conventional character of these calculations that to a large extent depend on the type of electric power plant and aggregates in use, natural conditions, time of complete loading, etc. For example, for the wind-driven electric power stations in Germany, LCOE varies from 3.9 to 13.8 eurocents per kW h [2]. We also recall that the renewable energy sources have a rather low density of energy flow; i.e., they require great expenses and areas for placement, strongly depend on weather conditions and the time of a day, are not very suitable for the major energy supply to large customers: cities and enterprises, which causes the necessity of extra power reserves.

Against this background, the competitive ability of nuclear power can be provided if its following obvious advantages are taken into account:

- stable generation;
- high power and high density of energy generation;
- fuel efficiency (the heating value is greater by millions of times than for organic fuel);
- durability and low operating costs;
- independence on volatility in organic fuel prices;
- absence of oxygen in carbon emissions.

However, these advantages can be taken into account only if nuclear power fulfills a few requirements. First, we mean unconditional *ensuring of safety* in the case of major accidents. This threat is a basic platform for the negative attitude to nuclear power, which some mass media and propagandists of alternative energy have hardwired or are painstakingly hardwiring into the brains of people. It is not accidental that, after the disaster in the Chernobyl nuclear power plant in April 1986, the growth rates of the global production of electrical energy by nuclear power plants decreased by six times. Second, we must *increase the economic efficiency* of nuclear power plants, which requires solving a series of scientific and technical problems which we consider further. Third, we should not forget that nuclear power is already *ecologically attractive*, since it is zero-carbon, and a tendency to zero-carbon energy is just about the primary concern at present. We certainly should ensure minimizing the threat of accumulation of radioactive wastes that are formed during the operation of nuclear power plants. In the coming years, it is desirable to transfer to a closed nuclear fuel cycle that would cut our demands for natural uranium and volumes of nuclear wastes.

The listed requirements can be fulfilled by *improving water–water energetic reactors (WWER), which are the primary ones operating today.* We note that no large accidents have occurred at the nuclear power plants in which the reactors of this type have been installed during the whole time of their operation. Nevertheless, after the events in 1986, the WWER structure was introduced with new additional safety barriers, although the disaster at the Chernobyl nuclear power plant occurred in a reactor of a different type (LWGR). Today we say that additional hydrogen recombiners inside a sealed shell, a containment that provides passive safety for power nuclear reactors, passive heat transfer that does not need electric power supply and control systems, and finally, a melt trap [3] that ensures localization and cooling of nuclear materials after a the most catastrophic type of disaster, which is active zone melting of a reactor, have become unique evidence of the enhanced security of the Russian WWERs.

Along with this, the extensive expansion of safety systems leads to a rise in the power unit price. In addition to safety, the economic efficiency of the Russian reactors and nuclear power plants that is required to maintain high export potential can be increased due to technical solutions that will lead stage by stage to the rejection of boron control and the use of zirconium alloys in the active zone, and will increase efficiency and breeding gain, which will reduce uranium consumption. In fact, we are referring to a new generation of WWER, WWER-S, in which the neutron spectrum is controlled in the active zone during the operation [4, 5] and a WWER-SCP coolant with supercritical parameters is used [6–8]. The possibilities of creating these plants and some others that we consider below are limited to a great extent by the characteristics of the available construction materials. Progress that predetermines the development of nuclear technology is required in the area of technical material science.

In the coming years, Russian nuclear power is expected to transfer to a new technological platform with a closed fuel cycle and solutions to the problems of spent nuclear fuel and accumulated radioactive waste (RW). In this case, nuclear power should become at least two-component: along with the major electrical energy producers, i.e., WWERs, a considerable part should be represented by nuclear power plants with fast neutron reactors that are able to ensure the production of nuclear fuel using natural (unenriched) or waste uranium, complete burning of minor actinides, and a drastic decrease in RW volumes.

The creation of two-component nuclear power brings into the foreground a set of problems that require theoretical computation and experimental studies due to the involvement of plutonium and minor actinides into the fuel cycle, the increase in the fuel burnup, specific heat power, and the fulfillment of radioecology and safety requirements.

The structure of a reactor unit of a new type must be integral. This will make it possible to localize even quite unlikely coolant leakages in the reactor vessel and to avoid the most dangerous event in nuclear power, which is a major disaster that requires evacuation of people with all the consequences that come with it.

We recall that today Russia is the only country in the world that uses fast neutron reactors and therefore has the required technological advantage, which we have lost in other industries. Keeping this leadership due to the development and use of progressive technological solutions, including sodium and lead-cooled fast reactor units, will contribute to maintenance of the export potential of the industry and to minimization of nuclear power risks related to the uncertainty of the energy market and resources provision [9, 10].

To increase the ecological attractiveness of nuclear power, the possibilities of accelerated *introduction of a nuclear fuel cycle with multirecycling of nuclear materials* including extraction and reuse of fissure components along with effective RW treatment before their burial are analyzed. Fractionation and reprocessing of spent nuclear fuel (SNF) together with "burning" of the most hazardous reaction products, such as minor actinides, is an integral part of such a strategy.

In addition to liquid-metal fast breeder reactors, other facilities with large fluxes of neutrons, e.g., molten salt reactors (MSRs), can be used for transmutation of minor actinides. The major and rather significant advantages of MSRs are the exclusion of the necessity of conventional fabrication of a pellet fuel, which is extremely difficult even for americium and almost unreal for curium, and the possibility of using without structural changes a broad range of fuel kernels, including plutonium and all minor actinides, including curium from accumulated spent nuclear fuel. Due to the high specific power density in the active zone and recirculation of molten fuel, complete burning of minor actinides occurs in MSRs quite effectively [11, 12].

The above substantiates the expediency of developing an MSR project ahead of schedule, not waiting for the introduction of fast neutron reactors to the energy system and the transition to two-component energy. Here, we should take into account that, in contrast to fast reactors, reprocessing of spent nuclear fuel using MSRs could be a new effective item of international business for Rosatom and our country, without requiring the construction of a large number of reactor facilities.

Figure 1 presents the scheme of nuclear fuel cycle closure without direct transition to fast neutron reactors, including with respect to the possibilities that already exist. It is seen that scheme provides for possible use of regenerated fuel of a different type, which can be technically implemented today and draws greater interest, including during the construction of new nuclear power plants.

Small nuclear power plants, which are expedient to be developed with respect to the low density of our country's population and the limited coverage of the territory by grid networks, could be another possible technological area in nuclear power development.

Potentially small nuclear power plants exist; they are well known and are not limited solely to the defense sector today. These are primarily the facilities of local energy or large individual consumers, such as metallurgical and oil-and-gas enterprises, ore-mining and processing complexes, airports, and harbors. Small nuclear power plants (SNPPs) can solve problems of energy supply to meteorological and hydrological stations, radiocommunication, radar location, and navigation support to the transport infrastructure in the Arctic Region. It is important that SNPPs can be a facility for export to the countries of Southeast Asia, Africa, and Oceania.

High capital investments in the construction of nuclear power plants mean LCOE growth, at a decrease in the plant capacity. Therefore, the rather old idea on putting into use small nuclear power plants has never been fulfilled until recently, despite the great number (more than 40!) of projects of this type. However, today we speak about the possibility to produce such plants industrially using ready-to-operate or fully shop-assembled structures, to produce them in lots in order to attain maximum (ideally complete) autonomy and thus to cut down considerably expenses for design, capital repair, and operation, as well as to minimize the service personnel.

Thus, if we can implement a mechanism when a ready-to-operate nuclear power plant is delivered to the installation place where it will be operated without the need for special service, including refueling and SNF discharge, and after the end of the service life, it is sent for disposal, the attitude to SNPPs as a commercially unattractive facility will change. We add that SNPPs could be in demand in remote areas for combined generation of heat and electrical energy (cogeneration), water desalination, and/or hydrogen production.

In recent years, we have been facing evident renaissance of the technology of hydrogen production and use for energy purposes, so-called hydrogen energy. It is true that the favorable solutions most interesting

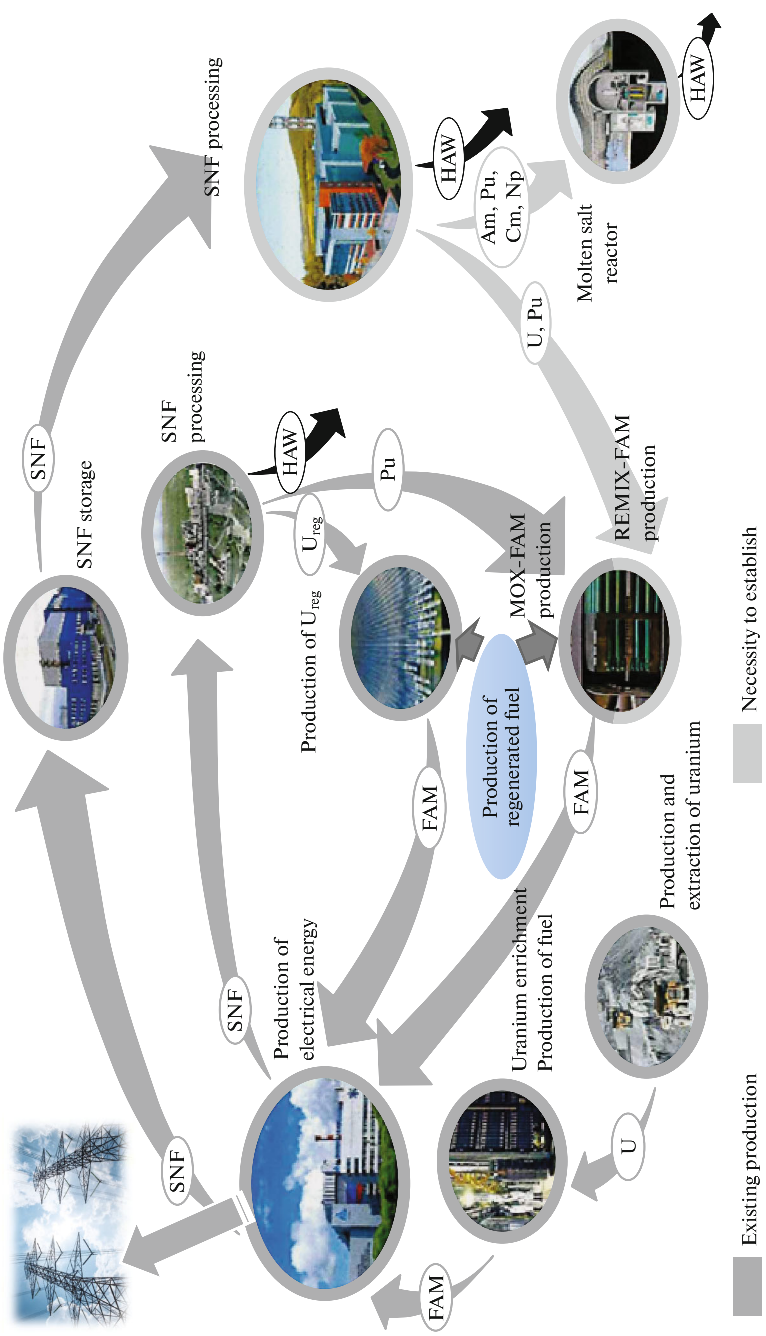

Fig. 1. Capacities and ways of closure of the nuclear fuel cycle.

economically and socially are based on the use of hydrogen in matters that are getting more urgent and are related to decarbonization of industry, transportation, and energy consumption and the necessity to install effective buffers—energy accumulators for increasing stability of energy systems, including the ones based on renewable energy sources. From this point of view, the scientific and technological activity aimed at expanding the scales of production and the use of hydrogen in the country's economy is necessary and well-timed.

Global production of hydrogen has been growing rapidly. According to the current predictions, in the 2050 perspective, its share in the structure of global energy may be up to 18%. In January 2017, at the World Economic Forum in Davos, an International Hydrogen Council was formed of the world's leading companies, including oil companies, that acknowledged that the large-scale use of hydrogen could be a new stage of energy development. At the conference on the problems of new energy in 2017, Prime Minister of Japan Shinzo Abe declared the intention to be the first to build a society based on hydrogen use and with time fully terminate the use of oil and natural gas as a fuel.

The idea of hydrogen energy is not new for our country; it was actively developed in the second half of the last century. The major obstacle to the large-scale use of hydrogen is the high energy-intensity of production and the explosive hazard of the oxygen–hydrogen mixture, which requires taking special measures, including during hydrogen storage/transportation in high-pressure bottles. These circumstances made the hydrogen use in energy and transportation economically unfavorable. A lot has changed since then. The changes related to scientific and technological progress had an influence on all elements of the hydrogen chain: production–storage/transportation–consumption. The extra generating capacities that have emerged necessitate organizing a flexible process of energy accumulation. Under these conditions, hydrogen production can be a universal and rather effective way of using extra capacities. Considerable interest is also directed to hydrogen fuel elements as a promising method of using hydrogen for transportation (for electric propulsion) and in mobile devices having a higher (by a factor of 3–6) energy density per unit weight compared to Li batteries and consequently an increase in the duration of operation without recharge. New effective hydrogen adsorbers have appeared for use in storage and transportation, such as solid (boron-containing) and liquid compounds based on metal nitrides and intermetallides, which makes it possible not to store hydrogen in high pressure bottles.

Rosatom has wide experience in hydrogen developments, including all elements of a hydrogen circulation life cycle. This makes it possible to swiftly join in a forming global trend. The most essential contribution to the development of hydrogen energy can be made by the nuclear industry at the stage of its large-scale production, which implies the use of a high-temperature gas-cooled reactor, the concept of which for the production of hydrogen in our country has long been well explored [13, 14].

We should mention separately thermonuclear fusion as a potential source of infinite energy. The arguments why we need to perform thermonuclear studies are the same as they were more than 60 years ago when we just started examining this problem. The key argument is the absence of carbon-containing emissions, the fundamental impossibility of reactor runaway (thermonuclear reactions are not chain), and the unlimitedness of fuel resources: it has been known since school days that the energy content of deuterium in a glass of water is equivalent to the energy content in a barrel of gasoline.

What has mankind done in order to master thermonuclear energy over the past years? Quite a lot. Today we have come close to the finish line: we can already demonstrate a capacity to produce thermonuclear energy, using though very complex devices.

Under construction in the south of France on the basis of a tokomak, the international thermonuclear experimental reactor (ITER) is without exaggeration the largest and the most expensive scientific project of modern times [15]. ITER is a collaboration among major global powers, Russia, the United States, the European Union, Japan, the People's Republic of China, India, and Korea.

Figure 2 shows the complex technological elements produced by different countries, including the collaboration members. Despite the fact that the project is being implemented and construction is underway, the first plasma will be produced in ITER only in 2025, and the tokamak will start operating with a deuterium–tritium mixture in the real mode no earlier than 2035. The question is why we have decided to produce such an expensive device. It is not just because of purely scientific interest, is it?

For our country, the following circumstance is of key importance: participating in this project under the contract, we gain access to the latest technologies that are not only Russian but also international. Each partner, including the Russian Federation, has a right to obtain royalty-free licenses for using the technologies developed within the framework of ITER. Therefore, today all collaboration participants, except for Russia, have their own national programs and projects funded at the level exceeding the contributions of these countries to the construction of ITER. Such national programs are necessary for developing and further use of the results and technologies obtained using the tokamak.

In Russia, the studies in the area of the specific fuel factor (SFF) are directed towards the use of "pure" thermonuclear fusion energy and the creation of

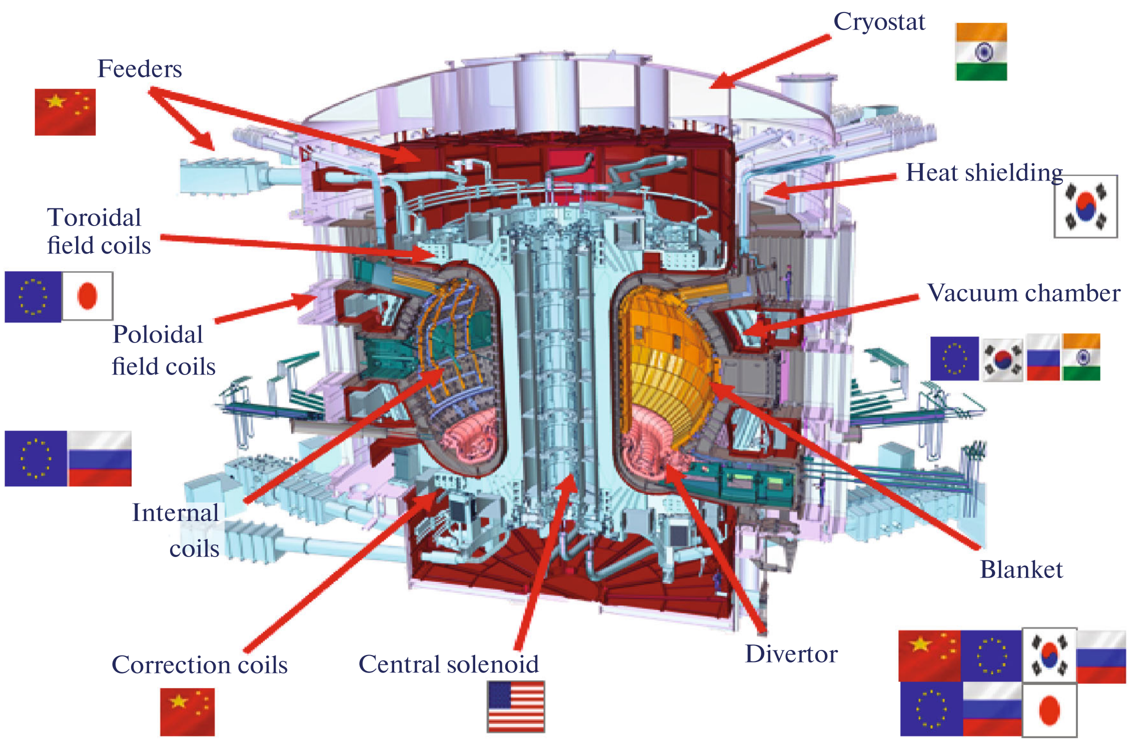

Fig. 2. Required elements of ITER tokamak and the countries-developers of these elements [9].

hybrid systems. The concept of a hybrid thermonuclear reactor should be considered together with the key problems of stable development in nuclear power and fuel cycle closure. The main advantage of this reactor compared to any other nuclear facility providing conversion of raw material isotopes to fissile isotopes is the use of high-energy thermonuclear neutrons, which allows an increase in the intensity of producing new fissile materials at equal capacities of the plants by almost ten times. From this it follows that the share of hybrid thermonuclear reactors in the structure of the nuclear energy system can be reduced to <15%, which solves the fuel problem in full [16, 17]. The fission reactors, which are the basis for the existing nuclear power, will be provided with fissile isotopes generated in the hybrid reactors. At the same time, the hybrid reactors will obtain tritium produced in the fission reactors. The second possible task of the hybrid reactors is highly effective complete burning of minor actinides accumulated as a result of operation of the nuclear reactors.

The works on inertial thermonuclear fusion, the principle of which is ignition (microexplosion) of a thermonuclear target for a time less than the time of its separation, stand apart. Such works allow moving forward to the region of superdense states of matter and superhigh energy densities, which is also of fundamental importance. We note that in addition to these technologies, thermonuclear fusion has demonstrated many secondary technological applications that have already been introduced in the industry.

The above areas of development of the nuclear industry are all based on promotion of Russian nuclear science and development of the high-tech sphere, which fulfills the requirements of the Strategy of RF Scientific and Technological Development for Provision of Energy and National Security of the Country. We emphasize that nuclear power has still been among the most high-tech knowledge-intensive branches of the national economy, providing economic surplus, which is rather noticeable in the budget of the country. In order to keep these positions, the branch should be dynamically developed according to the indicated trends that are included in the Nuclear Science, Engineering, and Technology National Project proposed by Rosatom for implementation.

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