

УДК 621.0

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**Аннотация**

Проводится анализ направлений развития АЭС, которые позволят реализовать программу по увеличению доли выработки электроэнергии за счет атомной энергетики в России.

**Ключевые слова:** атомная энергетика, атомная электростанция (АЭС), толерантное топливо (ТТ), управляемый термоядерный синтез (УТС).

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**ABSTRACT**

An analysis is being made of the directions for the development of nuclear power plants, which will make it possible to implement a program to increase the share of electricity generation through nuclear energy in Russia.

**Keywords:** nuclear power, nuclear power plant (NPP), accident tolerant fuel (ATF), controlled thermonuclear fusion (CTF).

The energy issue is important and fundamental for humanity. The need for electricity is growing every day, with an increase in the world's population. Today, electricity can be generated on an industrial scale in various ways. Traditional methods of energy generation, which got their name due to the use of traditional sources such as coal, gas and electricity generated by hydroelectric power plants, harm nature and human health in the process of energy generation [1]. Another way to generate energy through the use of renewable energy sources such as wind power, solar energy and others is called "green energy". "Green energy" has a poorly predictable energy production, as it depends on various natural factors that humanity cannot yet control, so this type of energy can only be used as an additional one.

There is a third way to generate energy – nuclear power. This type of energy production required many years of work of a huge number of scientists from different countries. Nuclear power has stable generation as it is not intermittent, since nuclear power plants can operate without interruption for a year or more without interruption or maintenance, which makes it a reliable source of energy [2].

And Russia has been and remains one of the world leaders in the field of nuclear energy. Thus, the world's first nuclear power plant was built in Obninsk (Kaluga region) (Fig. 1). It was equipped with a 5 MW uranium-graphite reactor of the AM type (Atom Peaceful). This nuclear power plant has been operating without accidents for about 50 years.

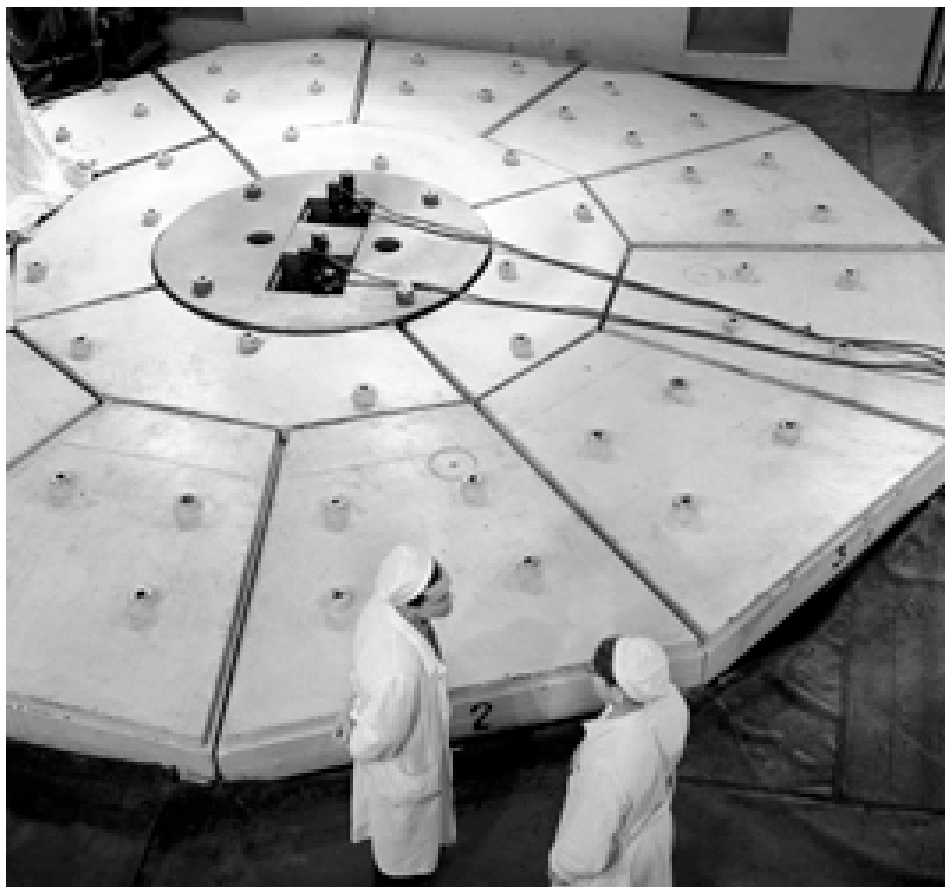


Figure 1. The reactor of the Obninsk NPP – the first nuclear power plant in the world. Photo: Valentin Kunov / ITAR-TASS. [Electronic resource]. <https://www.ippe.ru/images/1aps/reactor1.jpg>

Since the launch of the first nuclear power plant, nuclear power in Russia has not stood still, and today several nuclear power plants are operating in different parts of the country (Fig. 2), whose nuclear reactors collectively account for 9% of all nuclear reactors in the world, in addition, 10% of nuclear reactors operating for abroad, built according to Russian technologies.

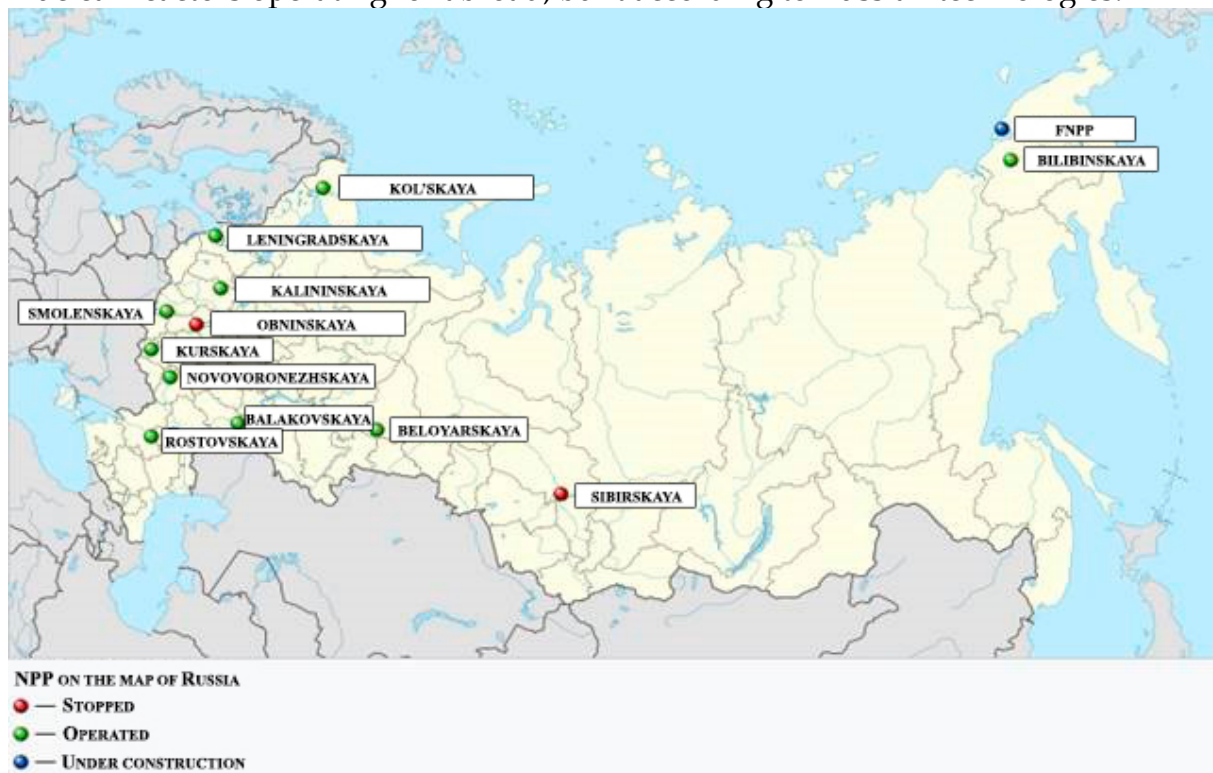


Figure 2. NPP in Russia. [Electronic resource]. [https://avatars.dzeninfra.ru/get-zen\\_doc/3437146/pub\\_5ff5a6bed1a90641ca257eba\\_5ff5a75baf142f0b178c19d2/scale\\_2400](https://avatars.dzeninfra.ru/get-zen_doc/3437146/pub_5ff5a6bed1a90641ca257eba_5ff5a75baf142f0b178c19d2/scale_2400)

And this is far from the limit of the development of the Russian nuclear power industry. Significant funds are being invested in further increasing the role of nuclear energy. So, in 2015, the total capacity of nuclear power plants in Russia was 24.2 GW and they generated about 16% of all electricity. At the same time, in the European part of the country, their share in the total output was 20%, and in the North-West – 39%. And according to Rosstat, in 2022, nuclear power plants already account for 20.2% of energy generation in Russia, which is 25% more than in 2015. Moreover, there is a task to bring the share of nuclear power plants in the total energy balance to 25% by 2045.

The complexity of implementing the program to increase the share of electricity generation through nuclear energy lies in the fact that during the time allotted for implementation, in parallel with the construction of new nuclear power units, high-power channel-type reactors that have exhausted their resource will be decommissioned. Therefore, the construction of new power units and the commissioning of new capacities should exceed the capacity of decommissioned reactors. This can be achieved through work in several directions.

The main direction is to improve the quality of the organization of operation. This includes measures to improve the reliability of the operation of power units, strengthen the leadership of managers, develop an integrated management system, improve discipline, qualifications and responsibility at all levels, as well as develop a safety culture. The next tasks include the transition of all power units from WWER -1200 to an 18-month fuel cycle. In order to increase the efficiency of electricity production, with the planned transition of the technical examination of equipment

once every 10 years on units operating in the design life, instead of four years, as was the case under the old rules [3].

Another area that is extremely promising is low power nuclear power plants (LNPP). They are interesting in that they require less space for construction, they can be built with minimal time and financial costs. They also make modular implementation possible, which ensures higher quality standards, to which all efforts in the development of nuclear energy are directed in the coming decades [4].

The next direction that will make it possible to implement a program to increase the share of electricity generation through nuclear energy is a qualitative change in nuclear fuel for nuclear power plants. And there are already results in this direction. On February 3, 2022, Rosatom announced the creation of a new nuclear fuel that is cheaper and safer than analogues. This is the so-called ATF (accident tolerant fuel) technology. This technology was created at "VNIINM" named after A.A. Bochvar (JSC "VNIINM", a part of the Fuel Company Rosatom "TVEL"). At the time of the demonstration of the development, experimental uranium disilicide fuel pellets for light water reactors, water-to-water power reactors (WWER) and power water reactors (PWR), were made. Nuclear fuel of a new generation of safety has increased heat resistance and low heat capacity, as well as high density and uranium content. This means that new portions of fuel will have to be loaded into the reactor less often, which correlates with the task of increasing the efficiency of electricity generation by nuclear power plants, which will also increase their overall productivity and reduce the cost of generated energy and heat. In this case, it will not be necessary to increase the enrichment in uranium-235. Low heat capacity with high thermal conductivity means less stored heat in the reactor core and lower fuel cladding temperature in emergency conditions. And the lower operating temperature of the fuel pellet compared to uranium dioxide improves the performance of the fuel.

Since 2019, Rosatom has been conducting reactor tests of ATF of Russian design for light water reactors. Experimental fuel assemblies (FA), which have passed three full cycles of reactor tests in the MIR research reactor at JSC "SSC RIAR", contain fuel elements with four options for combinations of cladding and fuel pellet materials. In September 2021, power unit No. 2 of the Rostov NPP began operating combined TVS-2M, each of which contains 12 ATF rods [5].

In general, all previous directions in the development of nuclear energy are focused on improving and increasing the efficiency of existing methods and technologies. But there are technologies that have been developed since the 50s of the 20th century to the present, which can bring nuclear energy to a qualitatively new level. And these areas also do not go unnoticed.

As part of the implementation of the program "Development of equipment, technologies and scientific research in the field of the use of atomic energy in the Russian Federation for the period up to 2024", additional allocations were allocated, which are directed to the development of controlled thermonuclear fusion technologies and innovative plasma technologies [3].

Controlled thermonuclear fusion (CTF) is the synthesis of heavier atomic nuclei from lighter ones in order to obtain energy (Fig. 3). CTF differs from traditional nuclear energy in that the latter uses a decay reaction, during which lighter nuclei are obtained from heavy nuclei. In the main nuclear reactions that are planned to be used for controlled thermonuclear fusion, deuterium ( $2\text{H}$ ) and tritium ( $3\text{H}$ ) will be used, and in the more distant future, helium-3 ( $3\text{He}$ ) and boron-11 ( $11\text{B}$ ) [6].

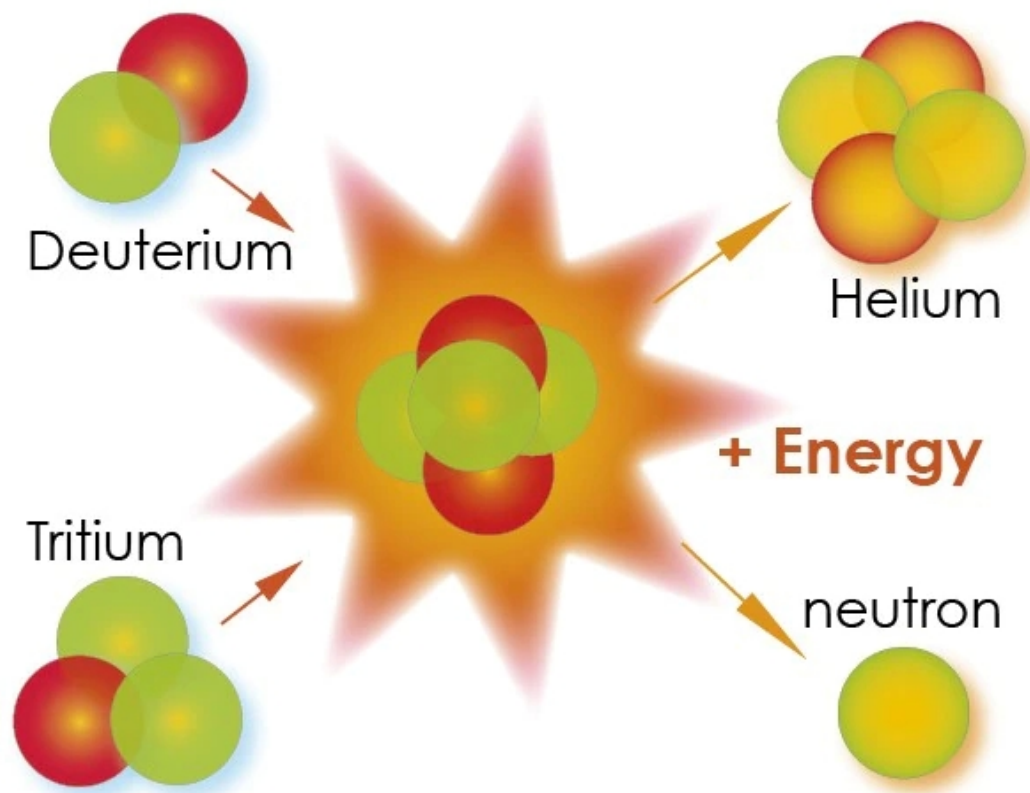
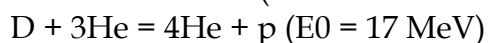
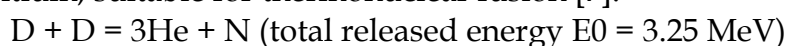


Figure 3. Nuclear fusion process. [Electronic resource].  
[https://www.swissinfo.ch/resource/blob/47503344/e974e2fc06438efc78245c4f359d13b6/nuclear\\_fusion-data.jpg](https://www.swissinfo.ch/resource/blob/47503344/e974e2fc06438efc78245c4f359d13b6/nuclear_fusion-data.jpg)

In the reaction in Fig. 3, the energy released per particle with a neutron mass is approximately 3.5 MeV. This is about 3-4 times more energy per particle released during the fission of uranium.

To date, other fusion reactions are being considered, in addition to the fusion of deuterium and tritium, suitable for thermonuclear fusion [7].



$3\text{He}$  is an isotope of the helium nucleus with a mass equal to 3,  $p$  is a proton (hydrogen nucleus). The deuterium fusion reaction  $D + D$  is good because there is as much fuel (deuterium) for it on Earth. The technology for separating deuterium from sea water has been developed and is relatively inexpensive. Unfortunately, the rate of this reaction is noticeably slower than the rate of the  $D + T$  (deuterium + tritium) reaction, so the  $D + D$  reaction requires a temperature of about 500 million degrees. For comparison, according to modern estimates, the temperature at the center of the Sun reaches "only" 20 million degrees.

The  $D + 3\text{He}$  fusion reaction is currently causing great excitement among people involved in space flights. It is known that there is a lot of  $3\text{He}$  isotope on the Moon, so the possibility of its transportation to the Earth is discussed as one of the priority tasks of astronautics. Unfortunately, the rate of this reaction is also noticeably lower, the rates of the  $D + T$  reaction and the required temperatures for this reaction are also at the level of 500 million degrees.

To contain plasma with a temperature of about 100-500 million degrees, an installation was developed that uses a magnetic field [8]. Such an installation was called a tokamak – from the initial letters of the Toroidal (that is, like a donut) Camera with Magnetic Coils. Such an installation allows using a magnetic field to keep in a suspended state a heated gas that has passed into an ionized state, the so-called plasma – the fourth aggregate state of matter along with liquid, solid

and gaseous. The Soviet scientist Igor Tamm was the first to develop the idea of a tokamak. The tokamak makes it possible to achieve the conditions necessary for the occurrence of controlled thermonuclear fusion. According to rough estimates, the appearance of a demonstration reactor at the TCF, which will be able to generate electricity, is expected no earlier than 2050. And if it turns out to be workable, then the first generation of commercial fusion reactors will appear in the 2060s or 2070s [9]. So, it will be, unless, of course, scientists find a breakthrough way to control thermonuclear fusion, which will speed up the creation of an appropriate reactor. But the Russian government is counting on breakthrough inventions in the field of nuclear energy, and therefore allocates funds to support developments in this direction. And obtaining a workable thermonuclear reactor, in the end, will repeatedly cover all the financial costs of its invention. Controlled thermonuclear fusion will make it possible to obtain a huge amount of energy from a small amount of matter (matter) and at the same time leave practically no radioactive waste, unlike traditional nuclear energy. The only significant by-product of fusion is helium. As a result of synthesis, there is no carbon monoxide (carbon monoxide – CO), carbon dioxide (carbon dioxide – CO<sub>2</sub>), sulfur or nitrogen oxides (SO, NO), or particulate environmental pollutants [10].

Nuclear energy in Russia is at a good level of development, more than 20% of all electricity comes from nuclear generation. There is also a program for the development and transition to a more advanced technology of controlled nuclear fusion, but while it is being developed, a program is being implemented to modernize and improve the existing traditional nuclear power industry in Russia. All actions of the government are aimed at maintaining stable generation of electricity, on which the operation of enterprises, the development of technologies and the comfortable existence of a person depend.

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