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ЯДЕРНАЯ ЭНЕРГЕТИКА ПОЛНОГО ЦИКЛА

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Аннотация

На сегодняшний день самым эффективным способом получения энергии является атомная энергетика полного цикла. В статье рассмотрен переход к использованию реакторов на быстрых нейтронах.

Ключевые слова: ядерная энергетика, ядерное топливо, тепловые элементы, тепловые нейтроны, быстрые нейтроны.

FULL CYCLE NUCLEAR POWER

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ABSTRACT

Nowadays, the most efficient way to generate energy is full cycle nuclear power. The transition to the use of fast neutron reactors is considered in the article.

Keywords: nuclear power, nuclear fuel, thermal elements, thermal neutrons, fast neutrons.

Every day population of the planet is increasing, and with it the demand for energy is growing. To obtain it, you can convert a different type of energy into the desired one or use fuel – a certain substance that, in course of certain processes, will release thermal energy, and thermal energy, in turn, can be converted into another type of energy. The simplest process when using fuel to produce thermal energy is combustion. And the simplest way to control this process is a fire with wood / charcoal as fuel. The thermal energy obtained by burning wood is quite enough for life in the countryside in a private household. But now in the same Russia, out of more than 140 million people, 75% live in cities, which roughly reflects world statistics [1]. And to cover the energy needs of the population in cities, much more efficient and large-scale ways of generating energy are required. Wood has been replaced with a more energy-intensive fuel and ways have been developed to burn it in order to get the maximum amount of energy from the minimum amount of fuel. For quite a long time, fossil fuels (coal, oil, gas, etc.) have been used as such fuel, mainly for economic reasons – there is a lot of this fuel, it is relatively easy to extract it and simply generate energy from it. But fossil fuels have a number of downsides. The first is a huge negative impact on the environment at all stages from mining to generating energy from it. The second is that the reserves of this type of fuel (coal, oil) were created in the earth's crust over millions of years, in fact being a non-renewable source of energy. Taking into account the constant growth in demand for energy and, as a result of the growth in production and consumption of this type of fuel, its reserves are decreasing, and every year this is happening faster and faster. These aspects have forced people to look for alternative ways to generate energy, other fuels. One of the alternatives has become "green energy", which uses renewable energy sources (RES): sunlight, water flows, tides, wind, geothermal heat. This energy converts various types of energy into electrical and thermal energy [2]. Green energy, having virtually endless resources for energy generation, has taken a fairly large percentage of the world's electricity generation over the past decades, mainly due to low environmental pollution during its production. But to take a leading position, at the moment, it is hampered by low performance and low reliability.

Another alternative was nuclear power, which originated in the 20th century. Nuclear power is an industry that now produces 10 percent of all electricity on Earth [3]. It is based on an extremely energy-efficient physical process of heat release – the fission of atomic nuclei. Uranium-235 is used as fuel. The mechanism of fission of the uranium nucleus was explained by L. Meitner and O. Frisch in 1939 on the basis of the drop model of the nucleus proposed by N. Bohr. The nucleus that has absorbed the neutron is in an excited state and, like a drop of mercury, when pushed, it begins to oscillate, changing its shape. When the excitation energy becomes greater than the binding energy, due to the Coulomb forces, the nucleus will break into two parts, which will scatter in opposite directions (Fig. 1).

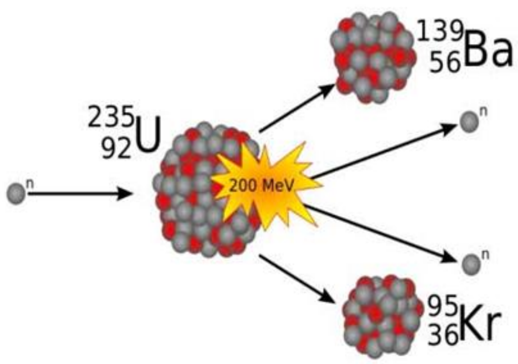

Figure 1. Mechanism of uranium nuclear fission. [Electronic resource]. https://fizclass.ru/wp-content/uploads/2015/08/delenie.jpg

The kinetic energy of new nuclei is due to the Coulomb forces. If the total binding energy of the fragment nuclei is less than the binding energy of the uranium nucleus, the reaction is accompanied by the release of huge energy in the form of the kinetic energy of the fragments, the energy of gamma rays and the energy of secondary neutrons.

In January 1939, E. Fermi suggested that during the fission of uranium-235 one should expect the emission of fast neutrons and that if the number of emitted neutrons is greater than the number of absorbed, a chain reaction is possible, i.e. there will be a sequence of nuclear reactions, where each subsequent nuclear reaction will be caused by a particle that appeared as a product of the reaction in the previous step. (Fig. 2). The theory of the presence of fast neutrons was later confirmed experimentally [4].

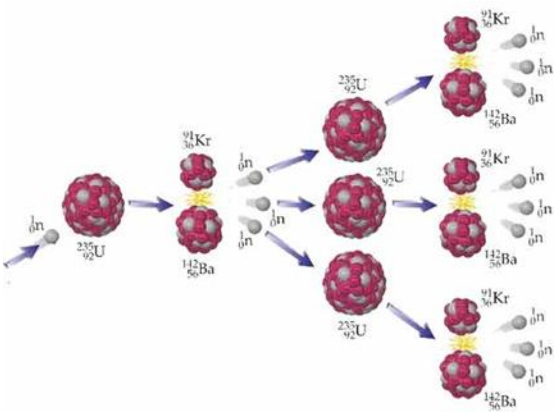

Figure 2. Nuclear chain reaction. [Electronic resource]. https://fizclass.ru/wp-content/uploads/2015/08/cepnaj.jpg

There are two types of chain reactions – controlled and uncontrolled. The main difference between controlled and uncontrolled chain reactions is that controlled chain reactions do not result in explosive effects while uncontrolled chain reactions result in an explosive release of energy. Uncontrolled nuclear chain reactions are used in atomic bombs. Controlled chain reactions are used in nuclear power plants to generate electricity, where a nuclear chain reaction is converted into a controlled chain reaction by controlling the number of fissile isotopes present, shortening the reaction time, and using moderators, i.e. the reaction proceeds completely under controlled conditions. Moreover, if a controlled chain reaction is brought to a state where the number of nuclear fission at each stage does not increase like an avalanche and does not decrease, such a reaction is called self-sustaining [5].

For a self-sustaining controlled nuclear fission chain reaction, an installation has been developed, called a nuclear reactor (Fig. 3), and also called a thermal neutron reactor or a slow neutron reactor. The main part of the reactor is its active zone, where nuclear fission takes place and nuclear energy is released. The core, usually in the form of a cylinder with a volume of fractions of a liter to many cubic meters, contains fissile material (nuclear fuel) in an amount exceeding the minimum mass required to start a self-sustaining chain fission reaction, called critical mass. Nuclear fuel is placed, as a rule, inside fuel elements, the number of which in the core can reach tens of thousands. Fuel elements are grouped into packages of several tens or hundreds of pieces. The core in most cases is a set of fuel elements immersed in a moderating medium (moderator) – a substance, due to elastic collisions with atoms of which the energy of neutrons that cause and accompany fission is reduced to the energies of thermal equilibrium with the medium. Such "thermal" neutrons have an increased ability to cause fission. Water (including heavy water, D2O) and graphite are usually used as a moderator. The reactor core is surrounded by a reflector made of materials that can scatter neutrons well. This layer returns the neutrons emitted from the core back to this zone, increasing the rate of the chain reaction and reducing the critical mass. Radiation biological shielding made of concrete and other materials is placed around the reflector to reduce radiation outside the reactor to an acceptable level.

To control the rate of the fission chain reaction, control rods made of materials that strongly absorb neutrons are used. Their introduction into the core reduces the rate of the chain reaction and, if necessary, completely stops it, despite the fact that the mass of nuclear fuel exceeds the critical one. As the control rods are removed from the core, the absorption of neutrons decreases, and the chain reaction can be brought to the stage of self-sustaining [6].

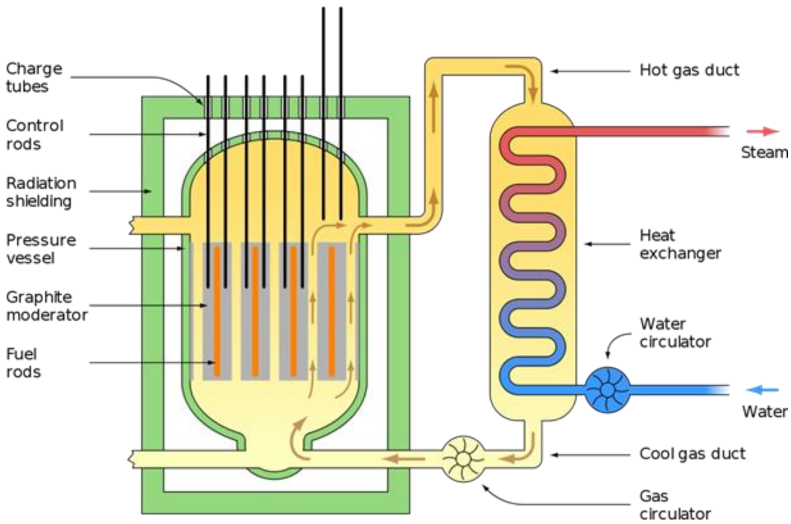

Figure 3. Nuclear reactor diagram. [Electronic resource]. https://www.kindpng.com/picc/b/716-7162631_nuclear-png.png

As a result of a self-sustaining controlled nuclear decay reaction in a nuclear reactor, a huge amount of energy is released, which heats the flowing coolant of the reactor – water, gas or liquid metal. Then the coolant transfers the received heat either directly to the reactor turbine, or to the coolant in the second circuit of the reactor, so that it already acts on the turbine. The turbine, in turn, transfers rotation to the rotor of the electric generator, the energy generated by it is supplied through transformers to the network. Thus, thermal energy from the decay of nuclei in the fuel is converted into mechanical energy, and mechanical energy into electrical energy. The process of generating energy at an NPP (Nuclear power plant) (Fig. 4) is one to one similar to a TPP (Thermal power plant) (Fig. 5), the only difference is in the fuel. But generating energy from nuclear fission is millions of times more efficient than burning fossil fuels. For comparison: in a large-capacity nuclear reactor, like the WWER-1000 (Water-Water Energy Reactor, WWER), which is common in Russia, approximately a ton of fuel burns out in a year, while thermal power plants operating on coal and oil products, consume two million tons of resources over the same period of time [3].

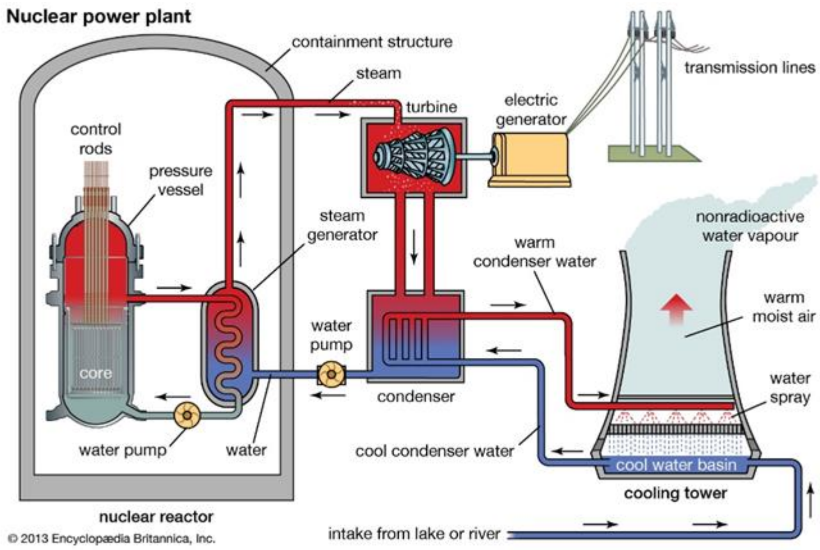

Figure 4. Nuclear power plant. [Electronic resource]. https://www.britannica.com/technology/nuclear-power

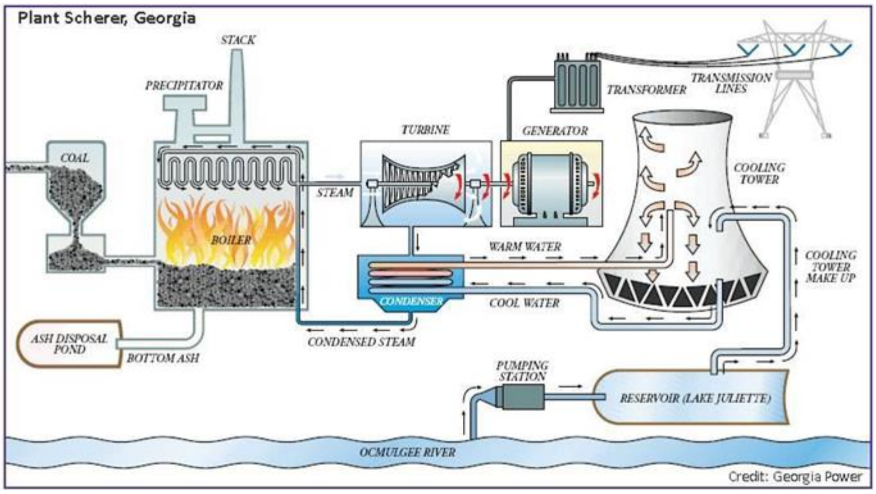

Figure 5. Thermal power plant. [Electronic resource]. https://mechanical-engineering.s3.amazonaws.com/monthly_2016_01/large.56a3ba56cfb34_ThermalPowerplant.jpg.c1a82cb4f047b3a4928e159dd147c393.jpg

Due to similarity in the construction of complexes, necessary devices, equipment and structures at thermal power plants and nuclear power plants intended for the production of electricity after thermal energy has been received, it would be possible to easily rebuild a thermal power plant into a nuclear power plant. Thus, increasing the efficiency of the entire complex for generating energy millions of times, and this would also contribute to a significant improvement in the environmental situation in the region. But such a transition does not occur for a number of reasons. The first problem is fuel supplies. Uranium is a finite resource, with more than 99% of natural uranium being uranium-238. and the share of uranium-235, which triggers a chain reaction of nuclear fission, in natural uranium is only 0.7%. The second problem is related to uranium mining. The distribution of uranium is uneven – two-thirds of the world's uranium production comes from deposits in Kazakhstan, Australia and Canada (Fig. 6) and does not form deposits. In total, the explored world reserves of uranium in the deposits amount to more than 6.5 million tons, and in general, the uranium resource is now estimated at 10.7 million tons. The content of uranium in the rock is low, and every year there are fewer and fewer deposits with a high uranium content. Now deposits are being mined, where the concentration of uranium ore in the rock is more than 0.01%, although until recently 0.2% was considered the threshold value [7]. That is, the spread of a super-efficient system for generating energy from nuclear fission, in the form of building new nuclear power plants and replacing thermal power plants with nuclear power plants, has stalled due to the extremely small amount of fuel, which is also difficult to extract.

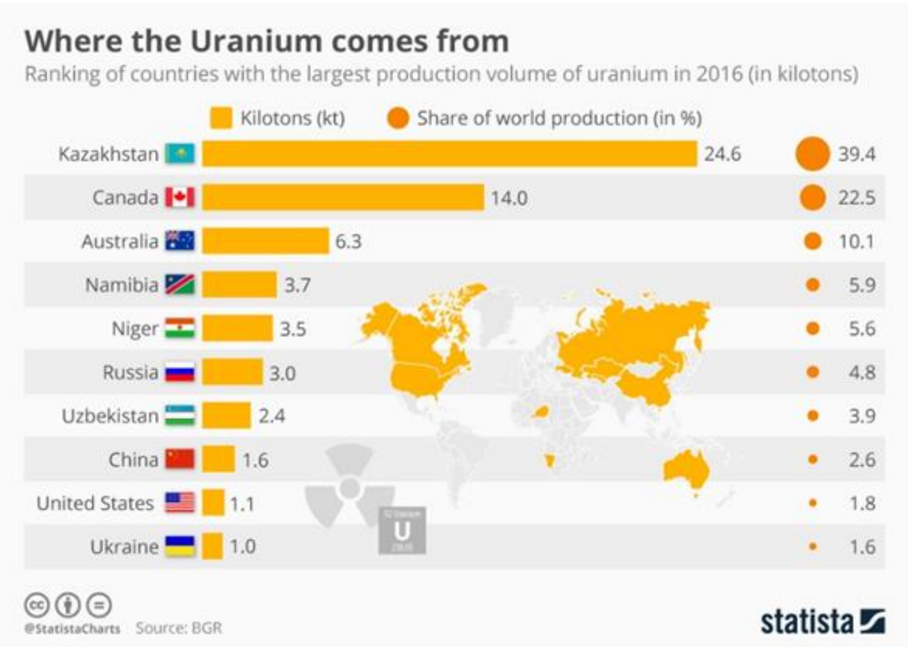

Figure 6. Where the Uranium comes from. [Electronic resource]. https://www.statista.com/chart/12304/countries-with-the-biggest-production-volume-of-uranium/

The third global problem is environmental and consists of spent nuclear fuel. Nuclear "waste" after passing through a Light-Water Reactor, which is the dominant type of reactor in the world today, consists of 97% unused fuel materials (Fig. 7) [8].

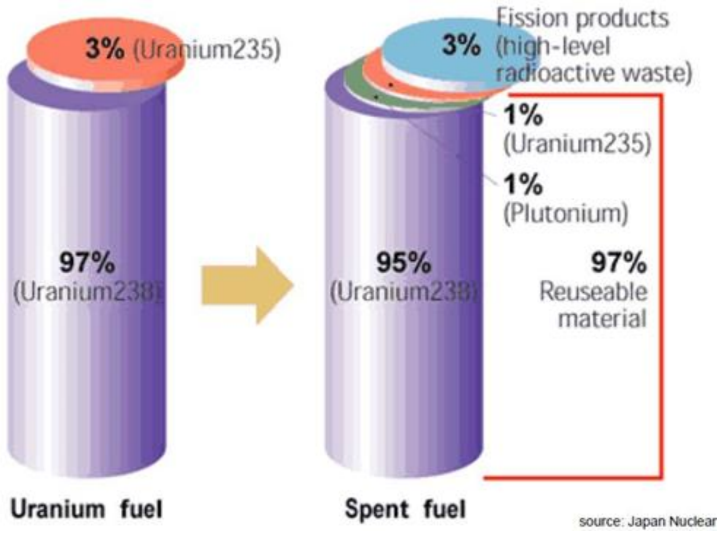

Figure 7. Composition of nuclear "waste". [Electronic resource]. https://qph.fs.quoracdn.net/main-qimg-1bdb9406f538d61ab7e857be20c50bac

Spent fuel is thermally hot as well as highly radioactive. Radioactive isotopes eventually decay, or disintegrate, to harmless materials. Some isotopes decay in hours or even minutes, but others decay very slowly. Strontium-90 and cesium-137 have half-lives of about 30 years (half of the radioactivity will decay in 30 years). Plutonium-239 has a half-life of 24,000 years. At the same time, very long after the spent nuclear fuel (SNF) is removed from the reactor, it produces lethal doses of radiation during short periods of direct exposure. For example, 10 years after removal from a reactor, the surface dose rate for a typical spent fuel assembly exceeds 10,000 rem/hour – far greater than the fatal whole-body dose for humans of about 500 rem received all at once. If isotopes from these high-level wastes get into groundwater or rivers, they may enter food chains. The dose produced through this indirect exposure would be much smaller than a direct-exposure dose, but a much larger population could be exposed [9]. And all this time, millions of years, it is necessary to store SNF somewhere, and in conditions that would allow avoiding SNF leaks into the external environment and would exclude the impact on the environment.

Given all these problems, a serious challenge was thrown to the world scientific community – to save nuclear energy by finding fuel to replace uranium-235. The problem was solved when a method was developed to convert uranium-238 into plutonium-239, which can be used to make fuel for a thermal neutron reactor. Plutonium is formed by the absorption of a neutron by a uranium-238 nucleus and the subsequent beta-conversion of uranium, first into neptunium, and then into plutonium. This is a different chemical element, and its separation from a mixture with uranium can be carried out by chemical means. But the only way to create powerful neutron fluxes is with a uranium nuclear reactor, in which there is a slow, non-explosive fission process, since the reactor mainly contains ordinary uranium-238. A small fraction of the uranium-235 isotope provides the fission process and the neutron flux for the conversion of uranium-238 into plutonium [10]. For such a transformation, a new type of reactor was developed, in the core of which there are no neutron moderators and subsequently called a fast neutron reactor. Moreover, a fast neutron reactor has a unique feature – a fast reactor is able to produce more fuel than it consumes. So, having spent 100 kilograms of a fissile isotope, you can get 120-130 kilograms of fresh nuclear fuel.

Because of this feature, fast neutron reactors are called breeders. Breeder produces plutonium not only for thermal neutron reactors, but also for himself.

Another potential advantage of the breeder is that it is a powerful tool for processing radioactive waste. During the reprocessing of fuel, radioactive waste is generated, for which it is necessary to build rather expensive storage facilities that can ensure their isolation from the environment for several million years. And if such radioactive substances are irradiated with fast neutrons, the time required for their isolation will decrease dramatically. And the costs are lower, and the benefit to the environment.

Thus, the breeder solves all the fuel problems that are facing today. First, as a result of a deeper and more complete use of uranium in breeders, the need for its extraction, and hence the impact on the environment, is reduced. Additional measures will make it possible to stop uranium mining altogether for quite a long time. Uranium will be obtained from spent nuclear fuel (SNF) and depleted uranium hexafluoride (DUHF), the reserves of which are more than sufficient. Secondly, the environmental impact of radioactive waste management is reduced. Radioactive waste requires the construction of expensive storage facilities to ensure its isolation from the environment for a long time. Breeders allow you to dramatically reduce the time required for their isolation and reduce the potential danger of waste. Thirdly, plutonium obtained during the processing of spent fuel from thermal neutron reactors can also be disposed of in breeders. The opposite approach (storage and final disposal of plutonium as radioactive waste) requires special safety measures and, accordingly, high costs [11].

Today, fast neutron reactors are no longer a theory, but a reality. In June 2021, the construction of the world's first state-of-the-art power unit belonging to the fourth generation, BREST-OD-300, began. The abbreviation BREST has a double interpretation: it is the name of a fast neutron reactor with lead coolant and at the same time the designation of the concept of a "fast" reactor, which has the property of natural safety Fukushima-1 nuclear power plant, March 11, 2011) will be impossible in principle. In the BREST concept, fast neutron nuclear reactors are designed in such a way that their safety will be based on the laws of nature, and not on the creation of additional engineering barriers and an increase in personnel. Its design excludes the so-called acceleration on prompt neutrons, which caused the Chernobyl accident. At BREST, the Fukushima scenario with the loss of coolant is also impossible.

This BREST reactor does not use uranium-235, which is less than one percent in nature. And the combination of the properties of dense nitride uranium-plutonium nuclear fuel and lead coolant makes it possible for BREST to operate in the so-called equilibrium fuel regime: when nuclear "fuel", plutonium, is produced as much as it "burns out". As part of spent nuclear fuel, it is used to manufacture new batches of fresh fuel for BREST, fed from outside only with waste (depleted) uranium-238, and so on in a circle. The cycle closes [12].

Mankind has come a long way in the ways of obtaining energy from burning wood to splitting atoms and is now on the threshold of the next revolutionary stage of development – obtaining energy in fast neutron reactors with a closed fuel cycle. The only thing hindering the ubiquitous distribution of such reactors so far is the relative high cost of the complex, in which these reactors are included, in comparison with thermal neutron reactors. But all the economic advantage of thermal neutron reactors now lies in the still relatively cheap extraction of uranium from the ground. As soon as the cost of uranium-235 production increases, and this will not be expected long, since, as mentioned earlier, its reserves are extremely small, and the deposits are depleted very quickly, the heyday of “fast” energy will come sharply – the era of fast neutron reactors.

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