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CLASSIFICATION OF NUCLEAR NPP REACTORS

The article deals with the classification of NPP nuclear reactors. A nuclear reactor is a device in which a chain reaction of nuclear fission of heavy elements uranium, plutonium, and thorium takes place, which controls and maintains itself. The possibility of such a reaction is ensured by the fact that each act of nuclear fission produces two or three neutrons capable of causing the fission of other nuclear fuel nuclei loaded into the reactor. In the reactor, simultaneously with the nuclear fission process, there is always, firstly, the absorption of neutrons by materials located in the active zone, and, secondly, the outflow of neutrons from the active zone of the reactor. These two factors make it possible to regulate the nuclear fission process so that the number of neutrons in the active zone and the number of acts of fission per unit of time are constant. Nuclear reactors are very diverse in terms of their parameters, purpose, design and a number of other features. Nuclear reactors can be classified according to the following main distinguishing features: the amount of neutron energy that causes nuclear fission; by type of retarder; according to the type and parameters of the coolant; by constructive execution; according to the compositional decision; by appointment. At nuclear power plants, nuclear reactors are used to generate electrical and thermal energy. At nuclear power plants, they are used to generate thermal energy for the purpose of heating and industrial heat supply. In ship power plants, they are used as sources of thermal, mechanical and electrical energy.

Key words: nuclear power plants, active zone, nuclear reactor.

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КЛАСИФІКАЦІЯ ЯДЕРНИХ РЕАКТОРІВ АЕС

У матеріалах статті розглядається класифікація ядерних реакторів АЕС. Ядерний реактор являє собою пристрій, в якому здійснюється ланцюгова реакція поділу ядер важких елементів урану, плутонію, торію, яка сама себе контролює і підтримує. Можливість здійснення такої реакції забезпечується тим, що кожен акт поділу ядра виробляє два або три нейтрони, здатних викликати поділ інших ядер ядерного палива, завантаженого в реактор. У реакторі одночасно з процесом поділу ядер завжди відбувається, по-перше, поглинання нейтронів матеріалами, що знаходяться в активній зоні, і, по-друге, витікання нейтронів з активної зони реактора. Ці два чинники дають можливість регулювати процес поділу ядер так, щоб число нейтронів в активній зоні і число актів поділу в одиницю часу були постійними. Ядерні реактори за своїми параметрами, призначенням, конструктивним виконанням і за рядом інших ознак дуже різноманітні. Класифікувати ядерні реактори можна за такими основними відмінними ознаками: за величиною енергії нейтронів, що викликають поділ ядер; за видом сповільнювача; за видом і параметрами теплоносія; за конструктивним виконанням; за компонувальним рішенням; за призначенням. На атомних електростанціях ядерні реактори застосовуються для вироблення електричної і теплової енергій. На атомних станціях теплопостачання вони використовуються для вироблення теплової енергії з метою опалювання і промислового теплопостачання. У суднових енергетичних установках вони застосовуються як джерела теплової, механічної і електричної енергій.

Ключові слова: атомні електричні станції, активна зона, ядерний реактор.

Introduction

The main strategic components of the modern global energy policy are man-made safety, energy efficiency, energy and resource conservation, which, together with other components, represent mandatory conditions for the ecological harmonization of the socio-economic development of mankind. Many states and interstate associations have experienced, on the one hand, the negative impact of the shortage of fuel and energy resources on the economy during periodic global fuel and energy crises, and, on the other hand, significant climatic and environmental changes due to technological development of traditional energy, developed fundamentally new concepts and approaches to energy and environmental security, energy and resource conservation. Recently, effective national and supranational energy agreements, strategies, plans, programs and new technologies have been developed, which make it possible to ensure significant savings in traditional fossil fuel and energy resources, to limit the use of some of them, in particular, hydrocarbons with a possible optimistic prospect of complete abandonment from them in the XXI century, to maximize the use of renewable types of energy, to solve the problems of global climate change on the planet as a result of warming by intensifying the process of reducing greenhouse gas emissions in order to achieve parity between emissions and their absorption by ecological systems.

One of the principles of the practical implementation of the world energy policy in nuclear energy, the impact of which on climate change is significantly less than that of thermal energy, is to minimize the probability of nuclear incidents and accidents at NPP power units while simultaneously increasing their thermal efficiency. This principle can be implemented due to a number of factors, including improvement and optimization of thermal schemes and parameters of technological processes of NPP power units with reactors of various types, optimal selection of modern and promising coolants and construction materials of active zones of nuclear reactors and steam generators, optimization of operating modes of NPP power units based on modern methods of mathematical modeling.

The strategy for the development of nuclear energy in various countries of the world, and in particular in the EU countries, includes planning not only the basic modes of operation of new powerful nuclear power units, but also the possibility of operation of these power units in modes of regulation of the daily schedule of energy consumption in energy systems with simultaneous provision of all modern criteria of increased security.

The need to ensure high requirements for the functional characteristics of power units of modern and promising NPPs is urgent.

The currently accepted way of using atomic energy at nuclear power plants is to convert this energy, using nuclear reactors and steam generators, into thermal energy of steam, which is then converted into electrical energy using steam turbines and electrical generators. Therefore, there is a great similarity between nuclear and thermal power plants from the point of view of the technological schemes of converting the thermal energy of the steam into the mechanical energy of the rotation of the turbine rotor and the electrical energy removed from the terminals of the electric generator. The difference between them lies in the technological processes of obtaining steam: for this purpose, thermal power plants (TPP) use boilers that convert the internal chemical energy of organic fuel into thermal energy of steam, and nuclear reactors and steam generators are used at nuclear power plants. The difference between them also lies in the fact that at nuclear power plants the main and auxiliary equipment is exposed to radiation, which complicates its construction, operation and repair [1].

A nuclear reactor is a device in which a chain reaction of fission of nuclei of heavy elements uranium, plutonium, thorium (^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{232}Th) is carried out, which controls and maintains itself. The possibility of such a reaction is ensured by the fact that each act of nuclear fission produces two or three neutrons capable of causing the fission of other nuclear fuel nuclei loaded into the reactor. In the reactor, simultaneously with the nuclear fission process, there is always, firstly, the absorption of neutrons by materials located in the active zone, and, secondly, the outflow of neutrons from the active zone of the reactor. These two factors make it possible to regulate the nuclear fission process so that the number of neutrons in the active zone and the number of acts of fission per unit of time are constant [2], [3].

One of the main characteristics of the reactor is its power, which is determined by the number of nuclear fissions per unit of time. The value of power, which is equal to 1 W, corresponds to division./s. 1 kg contains nuclei, the complete fission of which releases energy equal to J. Approximately the same amount of energy is released during the fission of 1 kg.

In general, a nuclear reactor consists of nuclear fuel, a neutron moderator and reflector, a coolant, regulating bodies (rods), control detectors, a casing, internal reactor structures, and biological protection. The central part of the nuclear reactor, which contains fuel, a moderator, regulatory bodies and a part of control detectors, forms an active zone through which the coolant is pumped.

Depending on the method of mutual arrangement of fuel and moderator in the active zone, reactors can be of homogeneous or heterogeneous type [4].

In a homogeneous reactor, nuclear fuel together with a moderator and coolant is a homogeneous (homogeneous) mixture in the form of solutions or melts, which is evenly distributed in the volume of the active zone and circulates in the circuit of the reactor installation.

In a heterogeneous reactor, the fuel is placed in the moderator in the form of individual elements located in the core. These elements are called heat-releasing elements (twels) and have different shapes and sizes.

Nuclear reactors are very diverse in terms of their parameters, purpose, design and a number of other features. Nuclear reactors can be classified according to the following main distinguishing features [5]:

– the amount of neutron energy that causes nuclear fission;

– by type of retarder;

– according to the type and parameters of the coolant;

– by constructive execution;

– according to the compositional decision;

– by appointment.

Reactors in which nuclear fission is caused mainly by thermal neutrons with an energy of less than 1 eV are called thermal neutron reactors. Reactors in which a large part of nuclear fission is carried out by fast neutrons with an energy equal to 0.5 – 10 MeV are called fast neutron reactors. There are also reactors in which nuclear fission is carried out mainly by intermediate neutrons with an energy slightly higher than the energy of thermal neutrons (about 6.7 eV) and which have a speed of about 30 km/c. Such reactors are called intermediate neutron reactors.

The fission cross section ^{233}U, ^{235}U, ^{239}Pu for thermal neutrons is hundreds of times larger than for fast neutrons. Therefore, thermal neutrons are much more effective for splitting the nuclei of these isotopes than fast neutrons. Using thermal neutrons, it is possible to maintain a chain reaction of fission in natural uranium, which contains only 0.714 % of this isotope, while it is impossible to carry out a chain reaction in natural uranium with fast neutrons, despite the fact that fast neutrons cause fission not only ^{235}U but ^{238}U also, the content of which in natural uranium is 99.28 %.

The aim of the work

The main strategic components of the modern global energy policy are man-made safety, energy efficiency, energy and resource conservation, which, together with other components, represent mandatory conditions for the ecological harmonization of the socio-economic development of mankind. One of the principles of the practical implementation of the world energy policy in nuclear energy, the impact of which on climate change is significantly less than that of thermal energy, is the minimization of the probability of occurrence of nuclear incidents and accidents at NPP power units while simultaneously increasing their thermal efficiency. This principle can be implemented due to a number of factors.

The need to ensure high requirements for the functional characteristics of power units of modern and promising nuclear power plants, which meet the criteria of increased safety, makes the following areas of scientific research relevant among others: system analysis of technological processes, structures and technical characteristics of modern and promising nuclear power reactors.

The general part

In fast neutron reactors, the concentration of fissile nuclides should be much higher than in thermal neutron reactors, so highly enriched fuel is used in them. Volumetric energy release in the active zone of fast neutron reactors is 500 – 1000 MW/m^3.

In reactors using thermal neutrons, the concentration of fissile nuclides is lower than in reactors using fast neutrons, so they use low-enriched (fissionable nuclide) fuel or natural uranium. Due to the presence of a large amount of moderator and lower concentration of fuel in the active zone of thermal neutron reactors, their volumetric energy release is significantly lower than that of fast and intermediate neutron reactors, and amounts to 120 – 130 MW/m^2.

A nuclear reactor must be considered not only as a device for the production of thermal energy, but also as a device for the production of new fissionable substances that are formed in the reactor simultaneously with the burning of nuclear fuel. Such substances are ^{239}Pu formed ^{238}U as a result of radioactive capture of neutrons by its nuclei and subsequent radioactive decays, and ^{233}U formed as a result of decays that follow the absorption of neutrons by ^{232}Th nuclei. They are formed as a result of the following reactions:

$$^{238}U + n \to {}^{239}Pu, \quad (1)$$

$$^{232}Th + n \to {}^{233}U. \quad (2)$$

Reaction (1) occurs in the core of reactors using the so-called uranium-plutonium fuel cycle, and reaction (2) occurs in the core of reactors using the thorium-uranium cycle.

Reactors, in the active zone of which are ^{238}U or ^{232}Th, belong to regenerative reactors that work with the reproduction of fissionable materials. The ratio of the number of atoms of a new fissile substance obtained in the reactor to the number of burned atoms of the loaded nuclear fuel is called the reproduction ratio. Reactors on fast neutrons are characterized by extended reproduction of secondary nuclear fuel, that is, they accumulate more fuel than is consumed. In reactors using thermal neutrons, the theoretical maximum value of the reproduction coefficient during fission of fuel nuclei is 1.10, and its actual value is always significantly less than this value.

Currently, all nuclear power plants of Ukraine use the uranium-plutonium cycle, which produces a large amount of spent nuclear fuel and radioactive waste, which consists of trans-uranium elements, including plutonium isotopes. Therefore, one of the ways to solve the problem of production and storage of a large amount of highly radioactive spent nuclear fuel and radioactive waste is the transition of the nuclear power industry of Ukraine to a safer thorium-uranium fuel cycle, which produces more than 10.000 times less radioactive waste compared to the currently used uranium plutonium cycle. This path is possible during the construction of new reactors and power units of nuclear power plants.

In thermal neutron reactors, substances with low atomic mass are used as moderators, which have a large elastic and inelastic scattering cross section and a small effective neutron absorption cross section. According to the type of moderator, thermal neutron reactors are divided into: light water (H_2O), heavy water (D_2O), graphite (C), beryllium (Be, BeO), organic (diphenyl and similar). Light-water, heavy-water and graphite reactors have become the most common.

In nuclear reactors, the slowing down of neutrons, which are formed in the process of fission of the nuclei of fuel atoms, is achieved by their collisions with the nuclei of the moderator atoms during the elastic scattering of neutrons in the moderator medium: with each collision with the nucleus of the moderator, a neutron gives this nucleus part of its energy. The average value of the energy loss of a neutron during one collision with the nucleus of a moderator atom is usually expressed as the average logarithmic energy loss ξ. The more ξ, the more effective the retarder. But for a complete characterization of the moderator, it is also necessary to take into account its ability to scatter and absorb neutrons, that is, the macroscopic scattering cross section Σ_s and the macroscopic absorption cross section Σ_a.

Retarders are characterized by retarding ability and retardation coefficient. The decelerating capacity of the decelerator is the product of the average logarithmic neutron energy loss and the macroscopic neutron scattering cross section $\xi\Sigma_s$. An indicator of the effectiveness of the retarder is the retardation coefficient, which is the ratio of the retarding ability to the macroscopic absorption cross section $(\xi\Sigma_s)/\Sigma_a$. Characteristics of some thermal neutron moderators are listed in Table 1.

Heavy water has the largest retardation coefficient of all thermal neutron moderators due to the very low value of the macroscopic neutron absorption cross section. Therefore, natural uranium can be used as fuel in heavy water reactors with a minimum critical load.

Table 1 – Properties of thermal neutron moderators

Retarder	Density or density, g/cm^3	Retarding capacity, cm^{-1}	Deceleration factor
H_2O	1.00	1.35	71
D_2O	1.10	0.176	5670
Graphite	1.60	0.060	192
Be	1.85	0.158	143

Light (ordinary) water H_2O has the best retarding ability due to the large value of the macroscopic neutron scattering cross section. Therefore, the dimensions of the active zone in light water reactors are the smallest. Nuclear fuel in light water reactors must be enriched, that is, have a sufficiently high concentration of fissionable nuclides, since ordinary water has a large macroscopic neutron absorption cross section.

The retarding ability of graphite is less than that of light and heavy water, so reactors with a graphite retarder have the largest dimensions of the active zone. The retardation coefficient of graphite is almost three times higher than that of light water, although it is significantly lower than that of heavy water. Nuclear fuel in graphite reactors must be enriched.

The disadvantage of retarders made of beryllium and its alloys is their toxicity and high cost, so they are rarely used.

The types and parameters of the coolants of nuclear reactors are largely determined by the thermophysical properties of the coolants themselves and the technical parameters and hydraulic schemes of:

– have good thermophysical properties to ensure the necessary heat transfer and high heat capacity;

– have a low neutron capture cross section;

– be compatible with construction materials;

– be heat- and radiation-resistant.

These requirements are largely satisfied by light (ordinary) water, heavy water, organic liquids (diphenyl, diphenyl mixtures), gases (helium, carbon dioxide, and others), liquid metals (sodium, potassium, lithium, their eutectic alloys, etc.).

Depending on the type and parameters of the coolant, nuclear reactors are divided into reactors with light water coolant, reactors with heavy water coolant, reactors with liquid organic coolant, reactors with gas coolant, reactors with liquid metal coolant.

Water (both light and heavy) has fairly good thermophysical properties. Most structural materials are relatively resistant to water in terms of corrosion and erosion. However, under the influence of radiation exposure, the processes of radiolysis (decomposition into oxygen and hydrogen) occur in water. Light (ordinary) water is widespread in nature, available and has a low cost. Due to its high cost, heavy water is used less often as a coolant.

In reactors of some designs, light water is both a heat carrier and a moderator, and water in these reactors can be in different aggregate states: in a liquid state without vaporization processes (without boiling), in the form of a steam-water mixture, and in the form of steam. Reactors of this type are divided into pressurized water reactors and boiling reactors. In pressurized water reactors, it is necessary to create a high water pressure in the coolant circuit (6 – 20 MPa) to ensure its liquid state at the temperatures reached in the reactors.

The use of liquid organic coolants makes it possible to have a pressure in the circuit of about 1.5 – 2.0 MPa. This pressure ensures the absence of vaporization of organic liquids at temperatures reached in the active zone of the reactors. However, under the influence of high temperatures and radiation exposure, organic liquids intensively decompose, which is their disadvantage as heat carriers.

Gas coolants have low heat output and heat capacity, therefore, for their effective use, it is necessary to increase the pressure in the circuit to 10 – 25 MPa.

Liquid metal coolants, along with good thermophysical properties that allow for a relatively low pressure in the circuit (1.5 – 2.0 MPa), have as disadvantages high corrosion aggressiveness, radioactivity caused by radiation exposure, and a high melting point.

By design, reactors are divided into the following types: shell, channel, basin [6].

Casing reactors are characterized by the presence of a casing, inside which a general flow of heat carrier flows, which washes all heat-releasing elements. In channel reactors, the coolant passes separately through each channel with the fuel assembly, its supply is carried out through individual pipelines. In pool reactors, the body is a large tank without a tight lid, which is filled with water for several meters. In the lower part of the pool there is an active zone through which the coolant is pumped [7].

According to this feature, all reactors are divided into three types: reactors with a loop layout of the equipment, reactors with an integral layout of the equipment, reactors with a block layout of the equipment.

The loop scheme of the layout of reactors is characterized by the presence of a large volume of the first circuit and long pipelines connecting the reactor, steam generators, pumps, volume compensators and other main equipment of the circuit. In the case of an integrated layout of the reactors, the reactor, steam generators and pumps are concentrated in one housing, and there are no pipes and pipelines. The block diagram of the layout of the reactors is characterized by the presence of short pipes of large diameter connecting the main equipment of the first circuit [8].

Conclusions

The classification of nuclear reactors by purpose is carried out depending on the scope of their application.

At nuclear power plants, nuclear reactors are used to generate electrical and thermal energy. At nuclear power plants, they are used to generate thermal energy for the purpose of heating and industrial heat supply. In ship power plants, they are used as sources of thermal, mechanical and electrical energy

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