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Prospects of Technological Improvement of Nuclear and Environmental Safety of World Energy

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Abstract

Today, the most urgent problem of the existing and future nuclear power industry is to ensure the nuclear and environmental safety of the operation of nuclear power reactor units (NPPs) and nuclear power plants (NPPs). It is solved thanks to the application of deeply echeloned protection and an anti-accident complex of methods and means for effective control of the operation of active reactor zones (AZR). However, the danger of existing NPPs in the world from time to time manifests itself in the form of severe post-project accidents and catastrophes with the release into the environment of a significant amount of radioactive materials dangerous for all living things. The results of the analysis show that the unconditional fulfillment of the main requirements of nuclear environmental safety and biocompatibility is possible only in the so-called wave nuclear reactor of the G-V generation, which, unlike reactors of the previous generations III, II+ and IV, does not require supercritical loading of the core with nuclear fuel. In the active zone of this reactor, nuclear-physical processes governed by physical law are implemented, which exclude the operator's participation in regulating the reactivity of the reactor's active zone, which makes it the reactor with the highest level of nuclear and environmental safety today, which is based on the principles of so-called internal safety, free from the human factor. The possibility of burning nuclear fuel based on U238 and Th232 in it expands the reserves of energetic nuclear fuel almost to inexhaustibility. The technology of nuclear reactors of the G5 generation through the secondary use of spent irradiated nuclear fuel (SNF) for the production of energy and energy raw materials with simultaneous burning of it to an environmentally safe state is able to quickly reduce the available stocks and further production of dangerous SNF, guarantee the nuclear and environmental safety of NPPs with reactors G5 and to technologically make nuclear post-project accidents and disasters impossible at the level of physical law with the complete elimination of the human factor.

Keywords

Nuclear-Environmental Safety, Nuclear Power Reactor Unit, Nuclear Fuel Cycle, Nuclear Technologies of the Fifth Generation, Nuclear-Environmental Safety, Wave Reactor, Biocompatibility

1. The Goal of the Article

To determine the most promising nuclear energy technologies, taking into account their highest nuclear and environmental safety and significant expansion of their resource and fuel base. Formulate the main fundamental principles of maximum nuclear and environmental safety for reactor energy technologies of the fifth generation G5 (Generation 5).

2. Relevance of the Article

A world opinion has formed, according to which the decisive criterion for the renewal of world nuclear energy should be the environmental factor. As such a criterion, we can take the concept of maximum reference safety with its quantitative indicator, which is determined by the values of the ratio of the concentrations of any man-made radionuclides and other environmentally harmful substances to their maximum permissible concentrations accumulated at the industrial sites of nuclear power plants and in the geospheric environments around nuclear power plants and at any what distances from them. In this regard, the theoretical foundations of new-generation nuclear power reactors are being actively developed, the concept of which involves the unconditional fulfillment of the main requirements of the standard nuclear-environmental safety and biocompatibility. The most promising among them is the so-called wave nuclear reactor, which, unlike the reactors of the previous generations III and IV, does not require supercritical loading of the core with nuclear fuel, and therefore, in principle, due to the laws of nuclear physics embedded in it, it cannot explode and cause the destruction of the reactor hall and therefore is a biologically and radioecologically safe reactor [1]. This reactor implements a non-linear self-regulating regime of a neutron-fission wave of slow nuclear combustion, which excludes the operator's participation, as a result of which this reactor has the highest level of internal safety.

Modern generations of NPPs were created and updated (in connection with the mass decommissioning of old NPPs, taking into account the end of their design operational resource) mainly on the basis of reactors of the VVER type, the number of which in the world nuclear power park is about 80% [2]. The efficiency factor (Efficiency) of operating nuclear power plants with VVER reactors does not exceed 30% - 40%, and the rest of the produced thermal energy is wastefully released into the environment. At the same time, there is a significant shortage of communal and high-temperature industrial heat in the world. The efficiency of burning nuclear fuel is also low [3] despite the fact that the world reserves of uranium-235, given the current rates of its consumption, will be enough only for the next few decades. Over the past 10 years, the current volumes of mining and processing of uranium raw materials are sufficient to meet the needs of nuclear fuel in the short term. The drop in global uranium prices had a significant impact on global uranium production in 2017-2018. But in the long term, in the case of growing demand for uranium, there will necessarily be a need for significant investments to improve technologies for its extraction and additional development of conserved deposits. As a result of neutron irradiation of nuclear fuel in the AZR in the process of the fuel company, highly active environmentally hazardous radioactive waste (RAW) is formed in the form of spent irradiated nuclear fuel (SNF). The problematic issues of its safe disposal and processing remain unsolved today, and therefore the safe handling of such hazardous waste requires a complex scientific, technical and industrial infrastructure [4] [5]. According to IAEA estimates, during the entire existence of nuclear energy, approximately 370,000 tons of highly radioactive and highly toxic nuclear fuel were produced in 14 countries of the world, which is stored for a long time at NPPs in holding pools for its cooling and radioecological aging. Of them, 120,000 tons were processed. Annually, global reserves of VOYAP increase by 10 - 20 thousand tons, and only 20% - 30% of this amount is processed. So, during the radiochemical processing of 1 ton of spent fuel with the aim of extraction of uranium and plutonium from it, 7500 tons of new solid and 1000 - 2200 tons of liquid radioactive waste, which is no less dangerous for nuclear power generation, is formed, requiring further storage and disposal. In order to process the remaining 250,000 tons of accumulated SWR, it will be necessary to engage in radiation production and then pour into the environment more than 400 million tons of radionuclide-contaminated water and unload approximately 250 million tons of solid hazardous waste from production. The construction of new NPPs and NPPs based on old reactor technologies is hampered by strong opposition from the world public. Traditional economic approaches and financial schemes for the construction of new NPPs and NPPs have lost their appeal today, and therefore new constructions of nuclear energy facilities are turning into very expensive long-term buildings. Such a situation raises doubts about the expediency of investments in modern nuclear energy, especially against the background of growing general skepticism in Europe regarding the further development of the mining industry. Therefore, the approach presented in the work regarding the creation of reference-safe nuclear energy is an extremely relevant problem today.

Experts primarily associate solving the problems of providing energy to mankind with thermonuclear reactors and nuclear reactors of the G-V generation, as well as with their hybrid variants—nuclear-thermonuclear reactors and In practice, these projects have not yet been implemented, but the prospects and significance of each of them for the further development of the world of nuclear energy will largely depend on which project will be implemented first and how early. Despite the mutual competitiveness of these two types of nuclear reactors, they both undoubtedly remain relevant and, if successful, will occupy their energy niche after their practical implementation. And their hybrid options, in the absence of appropriate technological alternatives and more efficient and safer nuclear energy technologies, would most likely become the basis of future world energy.

Opponents of the development of nuclear energy believe that as a result of its intensive development, the fuel resource of 235U will be exhausted in the coming decades. But at the same time, there is no warning that 235U will completely lose its validity if nuclear reactors that will effectively work on natural 238U are put into practice. This is determined by the fact that natural 238U is 140 times more abundant than 235U, and in this case it becomes profitable to extract uranium from low-enriched ores, the reserves of which are much larger, as well as other methods of its fabrication, for example, extracting fuel uranium from granite and marine water It is important to understand that wave reactors of the G-V generation have these capabilities, but at a significantly higher level of nuclear environmental safety when compared with fast nuclear reactors.

It should be noted that the new results of research into the kinetics and development of wave nuclear reactors, which are nuclear reactors of the new G-V generation, show that they can burn spent irradiated nuclear fuel (SNF), accumulated in large quantities as a result of the operation of previous nuclear reactors, more efficiently. Generations and then it is obvious that uranium resources become practically inexhaustible.

Of course, there are other important priority requirements, and a prominent place among them is nuclear environmental and radiation safety, which must be ensured in any uncontrolled situations with the complete exclusion of radioactive contamination as a reactor hall, an industrial site of a nuclear power plant, as well as any other, external to the NPP of the territories. And, in addition to everything, the NPP based on the G-V generation NPP is required to have an additional imperatively guaranteed safety margin in case of military and terrorist actions and attacks, which must be determined by the known maximum power density of the NPP per unit area, which does not deliberately lead to the formation of deadly radioactive and radiotoxic traces. From destroyed NPPs under any historically averaged weather conditions for each specific NPP location.

The concept of nuclear reactors of the G-V generation should provide the following two main requirements: - have the internal safety of the nuclear reactor and have nuclear-ecological biocompatibility with the Earth's biosphere. In this regard, it is possible to define a reference-safe reactor of the G-V generation, which, under any uncontrolled situation, does not create radioactive and radiotoxic pollution inside and outside the reactor hall, and in which the accident is extinguished not by the efforts of the human operator, but by the unwavering action of the immovables embedded in it physical principles and laws. At the same time, the concept of biocompatibility of a nuclear reactor is defined by the fact that the fission fragments most dangerous for the biosphere, such as technetium, iodine, cesium, zirconium, etc., transmute directly in the active zone of the reactor under the influence of neutrons and, as a result, turn into other biologically safe nuclei. To realize such biocompatibility, the transmuter reactor must be an intermediate neutron reactor.

It is proposed to include two types of nuclear reactors, which have so far only been proposed at the idea level, to the new generation nuclear reactors: 1) projects of subcritical nuclear reactors controlled by accelerators of charged particles ADS (accelerator driven systems); 2) nuclear breeder reactors on molten salts.

However, for the reasons given, wave reactors with internal safety and with the implementation of a neutron-splitting self-wave of nuclear combustion appear to be the most promising nuclear reactors. These reactors can be implemented as transmuter reactors. For example, a uranium-plutonium reactor with a lead moderator and coolant. Therefore, the wave reactors defined in this work, in the case of successful practical implementation, can most likely become full-fledged new representatives of reactors of the G-V generation [6]-[11].

In nuclear reactors of any type, the defining physical processes are neutron-nuclear reactions, which lead to the release of energy in its active zone, and the removal of heat from this zone, which is then used to produce electricity. An operating nuclear reactor is maintained in a critical state, when the number of neutrons emitted is such that the generated power is practically independent of time. In the subcritical regime, fewer neutrons appear than are lost, and the fission reaction quickly dies out. In the supercritical state, on the contrary, the neutron output is too large, and this can lead to heating and "explosion" of the active zone.

In traditional nuclear reactors, the critical state is physically unstable. It is artificially supported by a very complex control system. The absence of such a system will lead to the exit of the reactor to subcritical or supercritical regimes. The reactor is made with a reserve of reactivity/supercriticality, which is compensated by the introduction of special "excess" neutron absorbing rods into the active zone of the reactor. If, as the nuclear fuel burns out, the reactivity decreases, then the control rods are partially withdrawn from the system and the neutron flow increases to the value necessary for the planned and designed operation of the reactor. [12] [13] [14] [15]

The characteristic time of deviation from the critical state is determined mainly by the period of delayed neutrons released from fission fragments after some short time after the decay reaction. The duration of the period of delayed neutrons is less than one minute, and this property imposes very strict requirements on the quality and operation of the control system. During this short time, she must "take" and implement the appropriate decision and reaction in case of unforeseen situations.

The main idea of a reactor with internal safety is that the fuel components should be selected so that its characteristic time is noticeably longer than one minute and that self-regulation processes appear in the operating mode [16] [17].

In order to achieve such a mode of operation in the reactor, among all nuclear reactions, the following rather noticeable chain of transformations is necessary:

$$ {}^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \xrightarrow{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow{\beta^-} {}^{239}_{94}\mathrm{Pu}\,, \quad (1) $$

where symbols denote isotopes of uranium, neptunium and plutonium, - neutron - denotes beta decay. The process resulting from the plutonium reaction is the main one and is immediately used in the reactor core as fuel. The characteristic time of such a reaction is the time of two beta decays, which is approximately equal to days, which is almost four orders of magnitude longer than for delayed neutrons.

The self-regulating effect is related to the fact that for some reason an increase in the neutron flux causes a rapid burnout of plutonium and a decrease in its concentration and, accordingly, the neutron flux. And for the formation of new nuclei, it will proceed at the same rate for 3.3 days. And if suddenly, as a result of an external abnormal intervention, the neutron flow will decrease sharply and as a result, the rate of nuclear fuel burn-up will decrease, which in turn will increase the rate of plutonium production and build-up, with a further increase in the number of neutrons produced in the reactor core, after about the same time , is equal to several days.

The nuclear and environmental safety requirements of the new generation G-V reactors are fully met by the type of reactor with internal safety and biocompatibility [18]. Its most important advantage is the possibility to use as nuclear fuel natural or even technical uranium, as well as spent nuclear fuel in other reactors. Such a physical approach to nuclear and environmental safety makes it possible to exclude environmentally dangerous processes of nuclear fuel enrichment in the nuclear fuel cycle and to solve the problem of fuel resources for nuclear energy for hundreds of years in the future, besides solving the problem of accumulation and disposal of spent nuclear fuel in the biosphere. G-V generation reactors also lack a reactor reactivity control system, and the degree of nuclear fuel burnout can reach 30% - 70%. At the same time, it can be created as a reactor with a large fuel campaign, that is, it will work for tens of years without reloading its active zone with nuclear fuel. Thus, systematic studies of nuclear-environmental safety of nuclear energy technologies of the G-V generation were not performed, which emphasizes the importance and relevance of this work.

In the promising wave reactor of the G-V generation, the neutron-business wave mode of slow nuclear burning in a fissionable uranium-plutonium medium is realized. This new type of reactor makes it possible to eliminate the enrichment procedure of nuclear fuel in the nuclear fuel cycle and to use in it natural and even depleted technical uranium, as well as waste in the form of spent nuclear fuel in other reactors. Thorium can also be used as a material for nuclear fuel in this reactor [14]. And this is especially important both for Ukraine and for the new global nuclear energy industry, which will not need technologies for the enrichment of nuclear fuel materials. It also does not require a reactor reactivity control system, and the degree of fuel burnout can reach 50% - 70%, depending on the task and the requirements of the technical task. At the same time, the RBV can be implemented as a reactor with a fairly long fuel campaign without reloading the reactor with fuel.

The wave reactor of the G-V generation can also be implemented in the form of a biocompatible reactor-transmutator, which fully refers, for example, to the uranium-plutonium reactor of the new generation G-V with a lead moderator and coolant, or with a carbon moderator. This reactor is biocompatible with the environment, because the nuclides, fragments of fission reactions, which are particularly dangerous for humans and nature, will be transformed into less dangerous or safe nuclides when absorbing neutrons of resonant energies, and therefore the accumulation of spent nuclear fuel will not be so dangerous for the biosphere.

Experts sometimes refer to G-IV reactors as improved generation III and III+ reactors with passive emergency protective emergency cooling systems, BN-600 and BN-800 fast neutron reactors, which for many years will probably not yet occupy a basic place in the world nuclear energy. And the wave reactors developed so far are only theoretically classified as generation G-V reactors. It is obvious that the essence of the question is not in the name of the reactor generation, but in the fact that although the BN-600 and BN-800 have already been implemented in the form of several nuclear reactors, they are dangerous reactors at the fundamental physical level, just like the nuclear reactors of the III and III+ generations, because their active zones require supercritical loading of nuclear fuel. On the other hand, fast reactors would be able to solve the problem of a closed fuel cycle and this, at first glance, is a progressive technological path compared to generation II and II + I reactors. But fast reactors increase the possibility of unauthorized proliferation of nuclear materials.

3. Justification of the Obtained Results

For the renewal and development of the nuclear energy industry of Ukraine and the world against the background of the fourth energy transition to renewable energy sources, they have the potential to significantly reduce carbon emissions into the environment. It is extremely important to study the nuclear and environmental safety of reactors of the VVER type and, first of all, of their generations III and III+, including innovative AR-1000 reactors and small modular MMP reactors of the MP-160 type [2]. It is on the basis of such reactors that the development of Ukraine's nuclear power industry is planned. Therefore, further research is needed in order to provide a scientific and technical basis for modern priority tasks to improve the safety of NPPs with NPPs based on VVER-type reactors and, in particular, innovative AR-1000 and MR-160 reactors, as well as the development of conceptual foundations for the creation of next-generation G5 reactors [5], which should be based on the principles of maximum reference nuclear and environmental safety.

4. The Connection of the Author's Work with Important Scientific and Practical Tasks

In general, a detailed technological and environmental analysis of VVER-type reactors, taking into account the peculiarities of their operation in conditions of war and terrorist threats, confirms certain shortcomings that can directly affect their nuclear and environmental safety and which cannot be eliminated by modernizing their protective and emergency systems. As a result of a serious post-project accident at VVER-type reactors, radioactive materials may be released in an amount equivalent to several Chernobyl accidents. At the same time, all known nuclear disasters at power reactors confirm the special danger of the human factor [1] and misunderstanding of the physical nature of such disasters [15]. Modernization of nuclear reactors operating in the world envisages and implements the tasks of increasing the pressure in the reactor, increasing the operating temperature and increasing the fuel burn-up percentage. The consequence of such modernization and the operation of nuclear reactors in the extended, above-design mode of their operation is additional accelerated aging of the metal and a further decrease in the reliability and safety of the nuclear power plant. But industrial standards of nuclear enterprises do not always take this into account. All operating reactors in the world do not have specially created reliable methods and means of protection against terrorist and military attacks. There is also a danger of external influences of extreme irresistible natural phenomena—earthquakes and tornadoes, changes in the global climate, flooding, falling asteroids and other geospace phenomena. Presentation of the main material. Modern processes and technologies of the nuclear fuel cycle, as well as in the future for at least 2 - 3 decades, are technologically unprotected with regard to the guaranteed exclusion of the possible uncontrolled spread of nuclear materials [16]. Today, no country in the world has an ecologically acceptable technology for dealing with hazardous waste. As a result of radiochemical processing of 1 ton of spent fuel, in terms of uranium, 7500 tons of solid and 2200 tons of liquid radioactive waste (RAW) are formed, which also require further disposal and burial. Economically, this is unjustified and building such a processing complex in a country with a small territory is extremely dangerous. That is why more and more countries are inclined to abandon the processing of SWR and begin to consider it as a special type of RW. There is an opinion that deep geological repositories can be one of the safest options for long-term isolation of highly active waste from the environment and people. However, such an opinion does not have a sufficient ecological justification, which should take into account new knowledge in the field of astrogeophysics about the dynamics and nature of the energy activity of the deep bowels of the Earth. At the same time, the construction of one such repository, similar to Yucca Mountain, will cost tens of billions of US dollars and will take several decades. Therefore, the issue of creating new technologies for the absolutely environmentally safe neutralization and final disposal of VOYAP will remain unresolved for quite a long time. Deep burial of nuclear fuel should be carried out at horizons of up to 500 meters. However, even at such depths, a physical nuclear danger of new environmental accidents with unpredictable and uncontrollable environmental consequences may arise. There are no fissile materials in the decay products, and their burial under normal conditions is considered safe from the point of view of critical mass danger. But in a certain geological period, tectonic processes capable of compressing VTVZ may occur, and in VOYAP there is always a certain neutron field, and therefore later part of U-238 will turn into Pu-239, and tectonic compression of such a mass to its critical state can become dangerous. In the list of G4 reactor technologies, there are 5 projects based on the implementation of a closed nuclear fuel cycle (CFC) and one project of a high-temperature reactor with a gas coolant has an open nuclear fuel cycle (CFC). In the post-Fukushima period, it became obvious that the strategy of ZYAPC based on GIV fast reactors would not lead to absolutely safe nuclear energy. In addition, today the GIV program is not included in the budget and in the terms of its implementation. Therefore, in order to avoid the innumerable risks of nuclear weapons, experts strongly recommend nuclear powers to continue open nuclear weapons.

The industrial implementation of GIV closed nuclear fuel cycles requires the abolition of the non-proliferation policy for the operating countries, as well as a significant change in the existing programs and strategies of most nuclear countries. At the same time, any industrial use of GIV reactors based on ZYAPC requires huge capital investments in old, dangerous technologies for processing plants. In the conclusion of the leading specialists of the Massachusetts Institute of Technology regarding G-IV technologies, the conclusion was reached that the concepts of these technologies, their developers have not yet presented convincing materials regarding the reality of the declared advantages of ZAPC with processing of VOAP and focus on the growing risks of proliferation [17]. These studies have also shown that the cost of storage and burial of spent fuel is 4.5 times greater for the GIV incineration plant than for a single-use open-ended fuel cycle. Therefore, it is unrealistic that rapid GIV technologies with ZAPC will simultaneously solve the problems of high cost, safe disposal of waste and distribution.

5. The Scientific Novelty

Is that the concept of new nuclear energy and nuclear energy reactor technologies of the G-5 generation [5] with the maximum reference level of their nuclear and environmental safety for the future development of nuclear energy in Ukraine and the world must be based on physical laws that will allow implement the following main fundamental scientific-technical and engineering-physical principles:

- To use technical and unenriched natural uranium as nuclear fuel, as well as nuclear fuel accumulated as a result of the operation of reactors of previous generations for obtaining electricity and high-temperature industrial heat in order to replace hydrocarbon fuel, industrial production of environmentally safe energy resources and energy raw materials—hydrogen, synthetic motor fuel and lubricants, fresh water, fertilizers and other materials;
- The entire NPP is organized directly in the active zone of the G5 reactor with full self-regulation of the combustion processes of all the above types of nuclear fuel for the technological and engineering-physical impossibility of severe beyond-design accidents with the destruction of the reactor active zone [18] and radio-ecological disasters, as well as to solve the problem non-proliferation of nuclear technologies and dual-use materials;
- Unlike the reactor power technologies of previous generations, the active zones of reactors of the G-5 generation [17] should not have a supercritical load with nuclear fuel;
- By physical law to make impossible post-project accidents with their catastrophic nuclear-ecological consequences as a result of military and terrorist attacks;
- Non-competitive high cost-effectiveness of the design, construction and operation of NPP;
- Intra-reactor nuclear environmental safety and deepening of its technological foundations for biological compatibility and social acceptability of technologies at all levels of the new NPP;
- Complete absence of the human factor, reduction of capital, operational and post-operational costs through the use of serial materials and equipment with a minimum range, optimization of handling of radioactive waste and nuclear weapons, elimination of repair work and frequent reloading of nuclear fuel, minimization of the number of personnel, optimization of R & D costs;
- Guaranteed highest nuclear-environmental safety, which includes: full radio-environmental safety in any abnormal work situation; negligible radioactive contamination of the reactor hall; radiation exposure of personnel and the external environment.

6. Prospects for the Use of Research Results

In further research, special attention should be focused on the prospects for the development of global nuclear energy and ensuring its nuclear and ecological safety in the conditions of the fourth global energy transition and the transition to new safe nuclear energy technologies of the G5 generation. Such technologies, due to their engineering, physical and technical features, should significantly and positively affect the functioning and development of national and global energy security systems. In addition, we will achieve the main goal of the current global energy transition—zero impact on the global health of civilization and global climate security.

7. Conclusions

1) All generation II, III, III+ and IV reactors that are currently in operation have the potential for catastrophic accidents, the production of dangerous spent irradiated nuclear fuel (SNF), the possibility of uncontrolled spread of nuclear materials, the absence of an environmentally acceptable technology for processing SNF with insufficient justification environmental safety of any types of long-term storage of VOYAP, including its deep burial in geological rocks.

2) New safe nuclear energy technologies of the G5 generation will help to remove the issue of uranium fuel shortage for hundreds of years, which in turn will expand the raw materials for the production of cheap electrical energy and high-temperature heat practically indefinitely. In turn, this makes it possible to exclude from the nuclear fuel cycle the very complex process of enriching natural uranium and, at the same time, solve the problem of the accumulation of environmentally dangerous radioactive nuclear fuel and waste generated in the process of its processing. G5 technology by secondary use of SNF for the production of energy and energy raw materials, with its simultaneous burning to an ecologically safe state, is capable of quickly reducing the available stocks and further production of dangerous SNF, guaranteeing the nuclear and environmental safety of NPP with G5 reactors and technologically making nuclear accidents beyond design impossible and disasters at the level of physical law with complete avoidance of the human factor.

3) The study of the physical features of reactors of the G-V generation with internal safety and biocompatibility, which is based on the implementation of the neutron-scattering self-wave of nuclear combustion, has acquired special relevance today, which stimulated the solution of many important problems related to heat transfer processes, the structure of the active zone, the influence of the kinetics of radiation fuel defects and fuel phase state, thermal convection and mixing for liquid or gaseous nuclear fuel, radiation resistance of structural materials, modes of ignition/initialization of the active zone, etc.

4) In the scientific and technical literature, the possible designs of wave nuclear reactors of the G-V generation are already being discussed and the principled ways of practical solution to the technological possibility of realizing slow neutron-nuclear burning regimes in the active zones of new safe reactors are substantiated.

5) All the results of research on the kinetics of wave neutron-nuclear combustion were obtained for fast neutrons, that is, for fast wave reactors, and at the same time, the problem of the radiation resistance of the fuel cell wall, which should reach 500 s, was revealed. N. a., and it takes a lot of time to create struc-

tural materials for fuel cells with radiation resistance only up to 200 s. N. and, this problem became a difficult obstacle for the further development of fast reactors.

6) To solve the radiation resistance of the fuel cell wall, it is expedient to use neutrons with lower energy levels, in which the wave neutron-nuclear combustion regime could also be implemented, and this approach ensures a decrease in the radiation effect on the fuel cell wall and thereby fundamentally solves all problems of radiation resistance fuel tank walls.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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