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DEVELOPMENT OF NUCLEAR ENERGY AND SAFETY MEASURES IN MODERN NUCLEAR POWER PLANTS

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Abstract

The article provides information on the development of nuclear energy, chain reactions occurring in nuclear reactors, factors ensuring their continuous operation, the impact of ionizing radiation on the cells of living organisms, and the mechanisms of biological changes. Modern nuclear power plants (NPPs) play a central role in the transition to low-carbon energy systems; however, safety concerns remain a significant barrier to their widespread adoption. This paper examines risk assessment methodologies and the implementation of advanced safety measures in nuclear power plants. It is highlighted that various biological changes occur in the organism as a result of exposure to ionizing radiation.

Keywords: Nuclear reactor, chain reaction, nuclear fuel, ionizing radiation, biological impact, living cell, nuclear energy, risk assessment, safety measures, public trust, regulatory frameworks, passive safety systems, nuclear innovations.

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Introduction

Nuclear Fuel and Reactor Technology

At present, the main fissile isotopes used as nuclear fuel include uranium-235, plutonium-239, and uranium-233. Among these, only uranium-235 occurs naturally. It is found in natural uranium as a mixture of three isotopes: uranium-238 (99.282%), uranium-235 (0.712%), and uranium-234 (0.006%). Plutonium-239 and uranium-233 are produced industrially in nuclear reactors by neutron irradiation of uranium-238 and thorium-232, respectively. Among isotopes with threshold fission properties, uranium-238 is also used as nuclear fuel.

Each fissile material has a specific minimum mass at which a self-sustaining chain reaction can occur; this is known as the critical mass. The critical mass of a fissile substance depends on its geometric shape, volume, density, and the presence of impurities that may absorb or slow down neutrons without undergoing fission. For spherical uranium-235 with standard density and 95% purity, the critical mass ranges from 40 to 60 kg, while for plutonium-239 it ranges from 10 to 20 kg.

A nuclear facility refers to installations, complexes, or equipment in which nuclear materials are used. Nuclear materials are substances containing fissile nuclei. Radioactive materials, on the other hand, are substances containing radionuclides but not classified as nuclear materials.

All types of ionizing radiation (alpha, beta, gamma, neutron, and X-rays) have the ability to excite and ionize atoms and molecules of the materials they pass through; therefore, they are collectively referred to as ionizing radiation. Nuclear fuel is typically manufactured in the form of small pellets with a diameter of about 3 cm, which are placed inside special tubes. Each tube is called a fuel rod or fuel element (TVEL). These fuel elements are assembled into fuel assemblies (TVS), consisting of approximately 900 to 16,000 rods. Radiation shielding in reactors depends on their design and typically involves combinations of steel, concrete, polyethylene, and water.

Radiation-hazardous facilities include enterprises of the nuclear fuel cycle, such as uranium mining and radiochemical industries, radioactive waste processing and disposal sites, nuclear power plants, atomic thermal power plants, nuclear-powered installations, nuclear-powered ships, space nuclear systems, military nuclear power units, and nuclear weapons storage facilities.

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Nuclear reactors are generally classified into water-cooled reactors (such as VVER) and graphite-moderated reactors (such as RBMK and EGP types). In the lower part of nuclear reactors, radioactive iodine-131 (with a half-life of 8.04 days) may be present, which poses a significant health risk to humans. For safe operation, reactors must include iodine control mechanisms. The amount of atomic energy available on Earth is extremely large and practically inexhaustible. The estimated quantity of uranium in the Earth's crust is approximately 2.5×10^{12} tons, while the world's oceans contain about 2.5×10^{13} tons.

One kilogram of uranium-235 can produce as much energy as approximately 2.4 million kilograms of standard coal, while one kilogram of deuterium can replace about 16 million kilograms of coal. The use of nuclear energy requires the development of specialized sectors of mechanical engineering and also raises environmental concerns. Although nuclear power plants are significantly cleaner than conventional thermal power plants in terms of emissions, they still face challenges related to radioactive waste management and thermal pollution.

In Uzbekistan, the construction of a nuclear power plant (NPP) for electricity generation was officially launched on October 18–19, 2018, during the visit of the President of the Russian Federation, Vladimir Putin, and the President of the Republic of Uzbekistan, Shavkat Mirziyoyev. The first power unit of the NPP is planned to be commissioned by the end of 2028. The total cost of the project is estimated at 11 billion US dollars.

According to 2018 data, more than 470 nuclear reactors are currently operating in 35 countries worldwide. The electricity generated by these reactors accounts for approximately 25% (about 2,500 billion kWh) of the total global electricity production.

Nuclear Power Plants, Safety, and Biological Effects of Radiation

Nuclear power plants (NPPs) are considered one of the most efficient methods of energy production. However, in the event of technical failures or human error, accidents may occur, leading to the release of radioactive substances into the environment, which pose serious health risks. Therefore, it is essential to study international experience thoroughly in order to be prepared for such threats and effectively mitigate their consequences. Currently, more than 450 nuclear power plants are operating worldwide, with over 50 under construction. Nuclear power

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accounts for approximately 10% of global energy production. Most developed countries have been using this energy source rationally for many years while adhering to strict safety regulations.

NPPs operate based on nuclear reactions that release energy from atomic nuclei. This process mainly involves uranium or plutonium atoms. For use in nuclear reactors, uranium ore is first processed into powder, then formed into small metal pellets. These pellets are pressed into small capsules and sintered at temperatures of about 1500°C for several days. The resulting uranium pellets are then loaded into nuclear reactors. A single reactor may contain up to 10 million such fuel pellets.

Atomic nuclei emit neutrons, which in turn generate additional neutrons and particles with high kinetic energy. This energy forms the basis of nuclear power generation. During reactor operation, the released energy is converted into heat, which is transferred to a coolant (usually water). The heated coolant then transfers thermal energy to water in a secondary circuit through heat exchangers, producing steam. The generated steam drives a turbine, which in turn rotates a generator to produce electricity. The overall working principle of an NPP is similar to that of a thermal power plant, with the main difference being the method of steam generation.

The nuclear power plant being constructed in Uzbekistan in cooperation with the Russian state corporation “Rosatom” will consist of two power units, each with a capacity of 1.2 gigawatts. The project utilizes the advanced “VVER-1200 (Generation 3+)” reactor technology, which meets modern international safety standards. This plant is expected to become a major energy source not only for Uzbekistan but also for Central Asia. It is projected that the NPP will save approximately 3.7 billion cubic meters of natural gas annually and reduce carbon emissions by about 3 million tons per year. Additionally, exporting the saved natural gas could generate approximately 550–600 million US dollars annually.

Unlike thermal power plants, NPPs do not need to be located near large fuel sources. While transporting coal and gas is costly, the required nuclear fuel can be delivered in relatively small quantities. Moreover, spent nuclear fuel can be reprocessed and reused. However, there are two major challenges associated with NPPs: water supply and radioactive waste management.

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Regarding radioactive waste, specialists emphasize that waste volume can be significantly reduced through processing. However, the remaining waste must be safely stored, requiring specialized infrastructure and additional agreements. Another challenge is related to cooling systems, as cooling water requires additional energy, which can reduce the overall efficiency of the plant.

Nuclear fission energy is based on the splitting of heavy nuclei by neutrons, producing two smaller nuclei and several neutrons along with energy release:

$U\text{-}235 + n \rightarrow A_1 + A_2 + \nu + E$

Here, the released energy is approximately 200 MeV, and the average number of emitted neutrons is about 2.5, which allows a chain reaction to occur. Natural uranium consists of about 0.7% U-235 and 99.3% U-238. For a sustained chain reaction, neutrons must be slowed down to thermal energies (around 1/40 eV), which increases their likelihood of being absorbed by U-235. Therefore, moderators such as light water, heavy water, graphite, or beryllium are used in reactors. Fast neutron reactors, on the other hand, require enriched uranium with a higher concentration of U-235.

A nuclear reactor includes not only fuel and moderator but also coolant, structural materials, and control systems that regulate the chain reaction. Additional systems ensure radiation protection, coolant circulation, energy conversion, and fuel safety. Notably, approximately 1 gram of uranium can produce as much energy as about 3 tons of conventional fuel.

Biological Effects of Ionizing Radiation

Ionizing radiation affects biological tissues both directly and indirectly. Direct effects involve ionization and excitation of biomolecules, while indirect effects occur through the radiolysis of water. When radiation passes through water, it produces ions and free radicals such as hydrogen (H) and hydroxyl (OH), which are highly reactive.

These free radicals can initiate chemical reactions, including:

$H + H \rightarrow H_2$

$H + OH \rightarrow H_2O$

$OH + OH \rightarrow H_2O_2$

The formation of hydrogen peroxide and other reactive oxygen species leads to oxidative damage of biological molecules. The extent of radiation damage

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depends significantly on oxygen concentration, as higher oxygen levels enhance radiation effects.

Radiation can damage chromosomes directly or indirectly through chemical reactions. Cells with higher mitotic activity are more sensitive to radiation. According to Bergonie and Tribondeau's law, rapidly dividing cells such as lymphoid tissues, bone marrow, reproductive cells, and intestinal epithelium are more vulnerable, while tissues like muscle and nervous tissue are more resistant.

Radiation Safety and Modern Challenges

Today, radiation, chemical, and biological protection forces are considered an essential component of national security. Their importance is increasing due to growing threats such as technological accidents, environmental disasters, and international terrorism. These challenges affect not only military structures but also civilian sectors.

The situation is further complicated by the integration of various threats across military, environmental, and information domains. Therefore, the development of fundamental science is crucial for predicting and mitigating future risks. Improving radiation monitoring and assessment systems is essential for ensuring national safety.

A notable historical example is the 1978 "Cosmos-954" satellite accident, where a nuclear-powered spacecraft crashed in Canada, causing widespread radioactive contamination. This incident led to the development of advanced radiation detection technologies and monitoring systems.

Despite associated risks, nuclear energy remains a powerful and efficient source of electricity with minimal greenhouse gas emissions. However, major accidents such as Chernobyl (1986) and Fukushima (2011) have significantly influenced public perception and regulatory policies. Modern nuclear power plants aim to minimize risks by implementing advanced safety systems and risk assessment methodologies.

Risk assessment in nuclear power plants is aimed at ensuring plant safety and environmental protection through the analysis of hazards, their probability, and consequences.

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Probabilistic Risk Assessment (PRA). PRA is a quantitative method that determines the probability of failures in nuclear systems. It evaluates situations such as equipment failures and human errors and estimates overall risk levels.
Deterministic Safety Analysis (DSA). This method evaluates the response of nuclear systems to predefined accident scenarios such as loss of coolant or power supply and ensures that safety limits are maintained.
Integrated risk models. Modern approaches combine PRA and DSA methods with real-time data analysis, increasing predictive capabilities and preventing accidents.
Modern nuclear power plants apply advanced technologies to improve safety and minimize risks. Passive safety systems. Unlike traditional systems, passive safety systems operate without external power or human intervention. For example, the AP1000 reactor has a gravity-based cooling system that automatically activates in emergency situations.
Digital monitoring and artificial intelligence (AI). Artificial intelligence and machine learning tools monitor reactor conditions in real time. These technologies predict potential failures in advance and optimize maintenance schedules.
Backup systems and multi-layered protection. Modern reactors implement multiple layers of protection to ensure safety. For example, facilities are designed to withstand earthquakes or aircraft crashes.
The nuclear energy sector is subject to strict regulations to ensure safety and environmental protection.
International Atomic Energy Agency (IAEA). The IAEA sets global safety standards and reviews nuclear facilities within international cooperation.
National regulatory bodies. Countries such as the USA (NRC) and Japan (NRA) have developed strong regulatory systems to control nuclear power plant operations.
Harmonization of standards. It is implemented to unify international safety standards and expand opportunities for cross-border cooperation and technology transfer.
Despite technological advances, public acceptance of nuclear energy remains complex.

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Risk perception. High-profile incidents have increased concerns, but according to statistical data, nuclear energy is one of the safest energy sources.
Open communication. Dialogue and educational campaigns play an important role in eliminating misconceptions and building trust. For example, active engagement with the public in France has ensured strong attention to nuclear energy.
Public participation. Involving local communities in decision-making processes reduces resistance to projects and increases a sense of participation.
Case studies. Lessons learned from global practice.
Fukushima, Japan: After the Fukushima incident, Japan introduced strict regulatory rules and adopted advanced safety technologies and emergency response protocols.
Three Mile Island, USA: This incident demonstrated the importance of real-time monitoring and personnel training and led to significant changes in operational protocols.
Finland: Finland's Olkiluoto-3 reactor combines innovative safety systems and long-term waste management solutions, creating a model for new projects.

Conclusion

The success of modern nuclear power plants depends on a delicate balance between technological innovation and public trust. The application of advanced risk assessment tools and safety measures has significantly improved operational reliability; however, overcoming public concerns requires continued transparency and cooperation with society. In the search for sustainable energy solutions, the nuclear energy sector must prioritize safety and fully realize its potential in the global energy balance.
The solution to the energy crisis lies primarily in transitioning from the combustion of fossil fuels to alternative energy sources, in which nuclear power plants play a significant role. Under the influence of ionizing radiation, pathomorphological changes occur in the human body, which can be schematically divided into four groups: the development of dystrophic changes in various organs and tissues; hemorrhagic manifestations; suppression of hematopoietic organs; and infectious complications.

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This article examines risk management mechanisms, key innovations, and discusses the importance of transparency and collaboration in strengthening public acceptance.

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