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Research and analysis of new generation nuclear reactors in the world

Abstract. The research of new nuclear reactors is gaining urgent importance worldwide due to the need for continuous improvement of technologies to ensure safety, efficiency, and emissions reduction. This is crucial in the context of climate change and rapid technological development, which demand constant updating and improvement of nuclear energy. The objective of the study was to analyse next-generation reactors worldwide and identify their advantages and potential prospects for the future. The research utilized statistical, comparative, and analytical methods. The results of the analysis considered contemporary technological and safety parameters related to the operation of such reactors, including their ability to optimize fuel usage, enhance operational safety, and effectively manage radioactive waste. As a result of the study, fourth-generation nuclear reactors were analysed, including fast neutron reactors using gas cooling, very high-temperature reactors, reactors using sodium as a coolant, fast neutron reactors with lead cooling, reactors where the reaction occurs

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in molten salt, and supercritical water-cooled reactors. Each of these reactors has its unique features that make them distinctive in their application. For example, gas-cooled reactors have high productivity due to their ability to achieve high temperatures without significant pressure. On the other hand, molten salt reactors offer flexibility in using different types of fuel, including spent fuel, and can help reduce the level of radioactive waste through the use of special materials. During the analysis, it was noted that fourth-generation reactors, using various cooling and reaction-slowing technologies, are characterized by high efficiency, low accident risk, and the ability to produce stable electricity. Improved methods of reaction control open up new possibilities for the efficient production of electricity and increased safety in nuclear energy. The practical significance of the research lies in the opportunity to enhance modern electricity production technologies and ensure greater safety and efficiency in the field of nuclear energy

Keywords: nuclear energy; electricity generation; optimization of fuel use; cooling technologies; retarder; reactions

INTRODUCTION

Research on next-generation nuclear reactors plays a critical role in the development of the energy sector and ensuring stable and secure energy supply. The increasing interest in this topic is driven by the constant need for excellent, environmentally friendly, and efficient energy sources in the context of global challenges related to climate change, energy security, and sustainable development. In the modern world, urgent questions arise concerning the search for a sustainable and environmentally clean energy source. The development of nuclear energy and next-generation nuclear reactors plays a key role in addressing these issues. The study and exploration of this topic aim to ensure the safety and efficiency of nuclear energy use in the future. The accelerated development of new technologies in this field can open up new opportunities for energy development, reduce CO_2 emissions, and create a more resilient energy supply system. However, alongside the potential of next-generation nuclear reactors, there are serious challenges that require comprehensive consideration. In particular, safety issues arise concerning the effective management of nuclear materials and reactions. The development of new safety and monitoring systems, the search for optimal materials for reactor construction, and effective management of radioactive waste all require in-depth research and innovative solutions. It is important to address these aspects to create reliable and safe nuclear energy systems capable of meeting the energy needs of the modern world while caring for the environment.

According to the findings of I. Korduba & Zh. Patlashenko (2023), a promising type of next-generation nuclear reactor is a sodium-cooled reactor, due to its potential to provide a high level of energy production efficiency. The researchers note that this system has significant advantages in terms of nuclear fuel usage and ensures a more efficient energy generation process compared to other alternatives. The sodium-cooled reactor is known for its relatively high safety, a key aspect in considering new nuclear reactor technologies. Its ability to operate at high temperatures and maintain reaction stability reflects its potential as a long-term solution for efficient electricity generation.

In the studies of O. Yefimov *et al.* (2023), it was also emphasized that the sodium-cooled reactor demonstrates high efficiency in using recycled fuel and reducing the amount of waste. Its high degree of heat utilization and the ability to use spent nuclear fuel highlight its advantages in terms of sustainable and environmentally friendly solutions in nuclear energy. This type of reactor has the potential to enhance safety and reliability due to the specificity of its technical characteristics and operating principles.

In the work of E.M. Pysmennyi (2018), the importance of improving technological aspects of the supercritical water-cooled reactor was noted. He focuses on the necessity of developing and implementing innovative approaches aimed at increasing the efficiency, safety, and reliability of this type of reactor. The researcher emphasizes that this plays a crucial role in ensuring the stability and efficiency of nuclear energy, contributing to the development of more resilient and safe energy production technologies.

As noted by M. Ladan *et al.* (2023), a lead-cooled reactor based on fast neutron reactions is distinguished by an increased neutron slowing-down coefficient, contributing to higher spent fuel yield and reduced risks of reaction temperature escalation. According to statements, such a characteristic influences the overall safety of the reactor and extends its operational lifespan. The study also highlighted that the use of lead cooling contributes to the reduction of corrosion impact and enhances the reactor's resistance to external factors.

V.D. Polyakov & T.V. Donyk (2019) assert that a lead-cooled reactor utilizing the supercritical Rankine steam cycle demonstrates significant potential for efficient electricity generation. This approach creates conditions for the optimal utilization of the reactor's thermal energy potential, leading to an overall increase in efficiency. It was noted that the use of the Rankine cycle in combination with lead cooling contributes to the elevation of the working fluid temperature and ensures stability in the reactor's operation at high temperatures. These factors contribute to increased energy output and enhanced overall reactor productivity.

According to N.R. Kostyak (2022), another important aspect in the context of researching the new generation of nuclear reactors is not only the development of technological solutions but also the consideration of social and environmental requirements. The emphasis is placed on the need to implement strategies aimed at reducing environmental impact and increasing societal acceptability. Such an approach will promote not only the development of the energy sector but also the creation of more sustainable and acceptable energy solutions in the future.

Since the mentioned works did not conduct a detailed investigation into the specifics of all types of next-generation nuclear reactors, the aim of this research is to analyse all characteristics that determine the efficiency and safety of such reactors. Considering the wide range of factors influencing the operation of nuclear installations, this work aims to examine each reactor type to identify their distinctive features. A thorough analysis of specific details of different constructions will help determine the optimal direction for the further development of nuclear reactors. This approach will systematically evaluate the impact of each reactor type on meeting energy needs and ensuring environmental safety in the future.

MATERIALS AND METHODS

Within the conducted research, six main types of fourth-generation nuclear reactors were considered. These variations include:

1. Fast neutron reactor using gas cooling (GFR).
2. Reactor with very high temperatures (VHTR).
3. Reactor using sodium as a coolant (SFR).
4. Reactor with lead cooling (LFR).
5. Reactor with reactions occurring in molten salt (MSR).
6. Supercritical water-cooled reactor (SCWR).

The methods employed in the research encompassed statistical analysis, comparative analysis, as well as system-functional approach. These methods were applied to process and interpret data, providing deeper insights into the characteristics and operational features of next-generation nuclear reactors. The analysis of the obtained data allowed the identification of key aspects influencing their efficiency and safety, determining optimal directions for further refinement and optimization of reactor operations. The statistical method was utilized to assess data obtained during the investigation of nuclear reactors. This facilitated the identification of relationships between various reactor parameters and their functioning, as well as the determination of statistically significant dependencies among factors affecting their performance and safety. This method enabled the identification of potential and critical points in reactor operation, defining their operational characteristics and efficiency.

The comparative method allowed the extraction and identification of fundamental distinctions between different types of next-generation nuclear reactors. This method unveiled the advantages and disadvantages of each type, highlighting key characteristics influencing their efficiency and safety. The results of the comparative assessment can serve as a basis for selecting the most promising solutions for further advancements in new reactors. Additionally, this method emphasized important aspects that aided in a better understanding of the specific features and potential capabilities of each reactor, guiding directions for further research for maximizing the effectiveness of nuclear systems. System-functional approach, in turn, facilitated a deeper exploration of the specifics of each reactor type, including their main technical characteristics and parameters such as average power density, coolant mass flow rate, pressure inside the reactor, maximum coolant temperature, and others. This method revealed the dynamics of each reactor's operation, indicating their capabilities and limitations under specific operating conditions. It also allowed attention to be focused on critical aspects affecting the safety and reliability of reactor operations, as well as their overall efficiency.

Through the analysis, it was also determined that different types of reactors have their advantages and limitations. For example, high-temperature reactors with gas cooling may be more efficient in electricity and hydrogen production, while water-cooled reactors may offer greater versatility and have a smaller environmental impact. The obtained data formed the foundation for conducting further research and identified the main directions for improving reactor parameters to maximize their productivity and ensure the highest level of safety. Thus, statistical and comparative methods, along with system-functional approach, underscore the significance of further research and refinement in the field of next-generation nuclear reactors. These aspects reveal key factors influencing their efficiency and safety, emphasizing the need for exploring new solutions to ensure stability and enhance their functional characteristics.

RESULTS

The growing demand for clean and sustainable energy in the modern world stimulates continuous efforts to develop new technologies. The development of a new generation of nuclear reactors has become a priority to ensure efficient electricity production. One key aspect of this process is to increase the thermal efficiency of reactors, contributing to the optimization of converting nuclear energy into electricity. This is essential for expanding electricity production with minimal impact on the environment and natural resources (Şahin & Şahin, 2021).

Innovative development in nuclear energy aims to create a new generation of reactors with improved energy output while simultaneously minimizing negative environmental impact. Modern advanced technologies and reactor designs focus on increasing their thermal efficiency. This means that the efficiency of converting nuclear energy into electricity will be higher, making nuclear energy more competitive and suitable for widespread use. Such development opens perspectives for an energy system that demonstrates high stability and environmental preservation. This form of energy could be a significant step towards reducing carbon emissions and other pollutants, contributing to the preservation of environmental cleanliness.

Currently, the efforts of leading countries (such as the United States, Canada, Japan, and others) in the field of nuclear energy are directed towards creating the next generation of reactors within the framework of international initiatives. The main goal of this project is a significant increase in the thermal efficiency of nuclear power plants. Modern reactors have an efficiency of ~30%, while new Generation IV reactors have the potential to achieve rates of 45% and higher. This step could have immense significance for future energy consumption, providing a more sustainable and productive use of nuclear energy (Pioro *et al.*, 2019).

This significant collaboration between countries aims not only to expand electricity production, but also to transform this process into a more efficient and environmentally sustainable one. In particular, the initiative to develop new systems involves creating and implementing innovative systems aimed at increasing the utilization of nuclear fuel. It is expected that with the increase in the thermal efficiency of reactors, electricity production will be more efficient using the same amount of fuel.

It is worth noting that the creation of a new generation of Generation IV reactors has a broad spectrum of goals, including improving the safety and reliability of reactor systems. In addition to increasing energy production, these reactors are oriented towards using advanced technologies to minimize potential risks of nuclear accidents. Their innovative approaches cover not only technical aspects, but also the creation of comprehensive control and protection systems aimed at preventing potential problems. This fundamental development has significant potential to improve safety and reliability standards, contributing to stable and safe electricity production worldwide.

The International Generation IV Forum program has consolidated possible design concepts for nuclear reactors into six main types (Kamide *et al.*, 2021). These variations of nuclear reactors differ from each other in design, neutron type, reagents used, coolant, operating temperatures, and pressures, providing them with unique characteristics.

Gas-cooled fast reactor. GFR (HTR) is a complex system based on the use of fast neutrons to generate electricity. The power of this system lies not only in the generation of electricity, but also in the possibility of using it to produce hydrogen (Fig. 1).

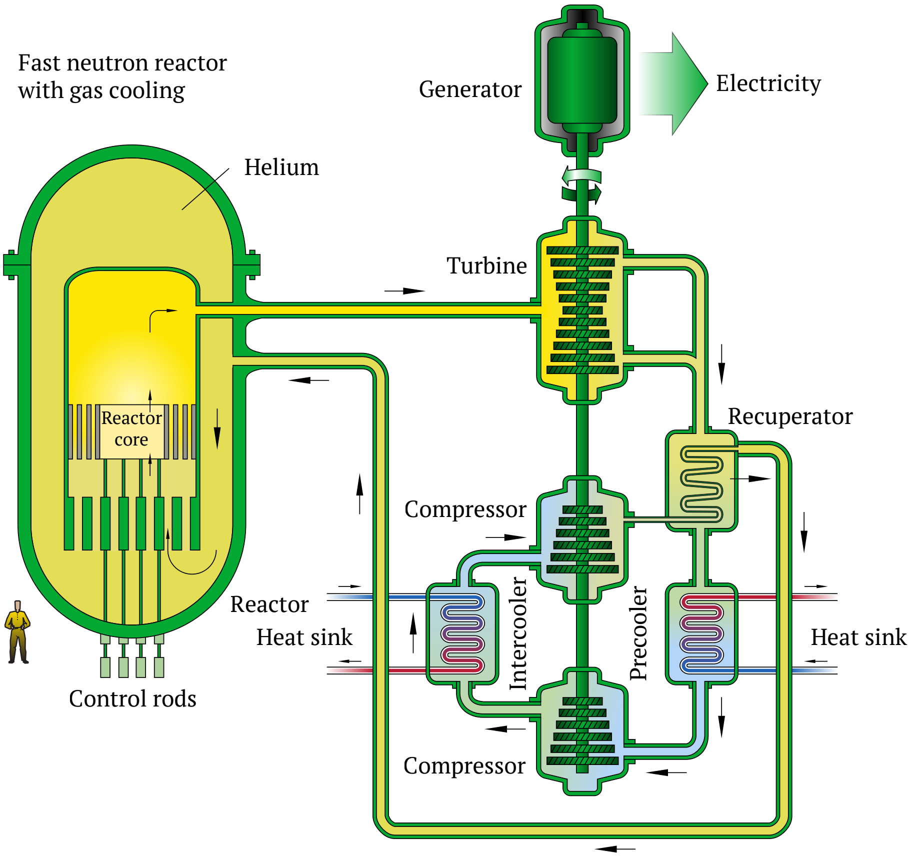

Figure 1. The concept of a nuclear power plant based on GFR

Source: W. Jung (2023)

Helium is the primary coolant in this concept. The net thermal efficiency of this system is approximately 48%. The main characteristics and parameters of this concept are provided in Table 1. It is also noteworthy that due to the challenges associated with implementing the direct Brayton gas turbine cycle with helium used in this system, alternative options using indirect cycles and other technological solutions are being considered. Transitioning to indirect cycles means moving from the direct use of helium gas, which operates directly in the turbine system, to the use of heat exchangers that facilitate interaction between the reactor and the working fluid of the gas turbine systems. This implies that the heat generated in the reactor is first transferred through a heat exchanger, where it is used to heat another working fluid, and only after that is this working fluid utilized to increase steam pressure in turbines that generate electricity (Čížek *et al.*, 2021).

Table 1. The main design parameters of the GFR concept

Reactor parameters	Unit of measurement	Reference value
Reactor power	MW	600
Coolant inlet/outlet temperature	°C	490/850
Pressure	MPa	9
Mass consumption of the coolant	kg/s	320
Standard fuel mixture	-	Uranium-plutonium ceramics (70/30%)
The net efficiency of the installation	%	48

Source: W. Jung (2023)

This allows for improved heat exchange and heat exchanger performance, allowing more efficient use of the heat generated in the reactor to produce electricity. Such a transition may be more difficult to implement due to the need to create an additional heat exchange system and process optimization, but it can provide an opportunity to improve the working process and increase the overall efficiency of the reactor.

Very-high-temperature reactor. VHTR is a reactor used to generate electricity and produce hydrogen through high-temperature electrolysis (Fig. 2).

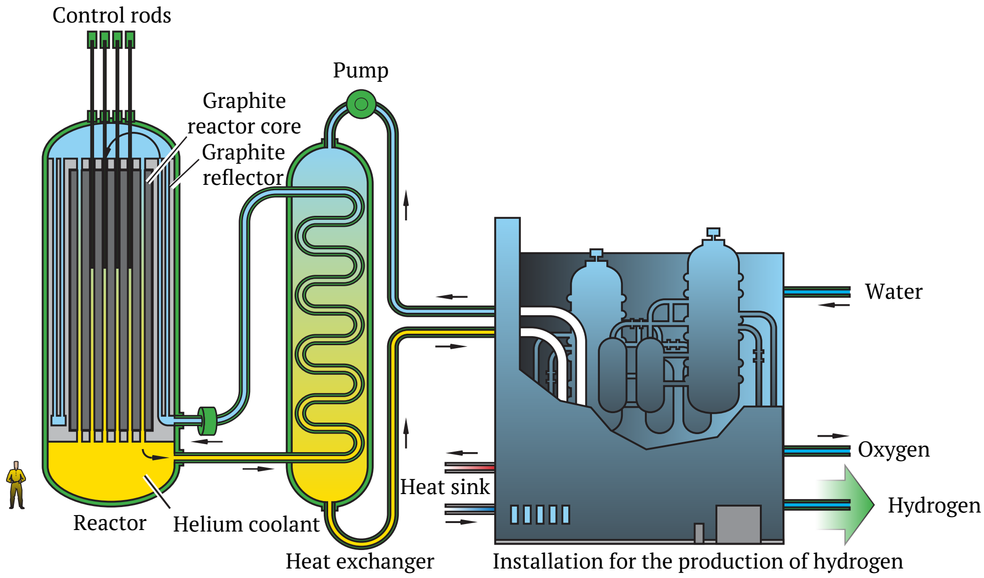

Figure 2. Concept of a facility with a VHTR combined with hydrogen production

Source: G. Baccaglini *et al.* (2003)

The foundation of this design is the use of a graphite moderator and helium as the coolant. During reactor operation, helium is heated to a temperature of 640°C at the inlet and 1000°C at the outlet at a pressure of 7 MPa. This ensures a high level of thermal efficiency exceeding 50%. More detailed parameters and structural characteristics of the VHTR are provided in Table 2.

SFR, which is like the GFR in certain aspects, is another unique reactor operating with fast neutrons. The primary objectives of this reactor type include electricity generation and the management of high-level radioactive waste. However, the distinctive feature of the SFR lies in its ability to use liquid sodium as a coolant, maintaining a temperature range from 530°C to 550°C at atmospheric pressure. The uniqueness of this approach lies in the reactor's capability to work with various types of fuels, including both oxide and metal fuels, making it more versatile in application and operation (Ohshima & Kubo, 2023). It is worth noting that Japan has been utilizing SFR at the Monju Nuclear Power Plant for an extended period (Fig. 3).

Table 2. The main design parameters of the concept of a VHTR

Reactor parameters	Unit of measurement	Reference value
Power	MW	600
Inlet coolant temperature	°C	640
Outlet coolant temperature	°C	1000
Heat carrier consumption/mass consumption	kg/s	Helium/320
Reference fuel composition	-	ZrC-coated particles
The net efficiency of the installation	%	More than 50

Source: G. Baccaglini *et al.* (2003)

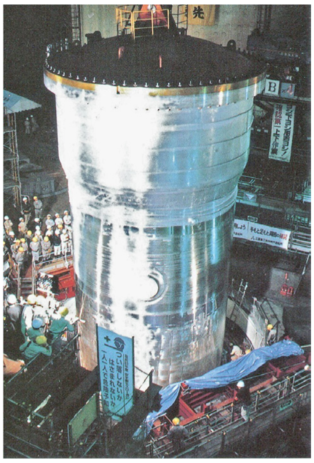

Figure 3. Photo of the SFR reactor housing at the Monju NPP (Japan)

Source: I. Pioro & P. Kirillov (2013)

In the aforementioned systems, electricity generation occurs through heat exchange within the system. Utilizing heat exchangers, high-temperature SFRs interact with sodium as a coolant. This process takes place at low pressure, generating thermal energy used to produce steam. Subsequently, the steam is employed in the Rankine steam cycle, where it expands, performs work, and adds energy to steam generators. The aim of such a system is to optimize the efficiency of converting the thermal energy resulting from the reaction in SFR into usable electricity by utilizing the Rankine steam cycle under low pressure (Fig. 4). The key parameters of the overall SFR concept are outlined in Table 3.

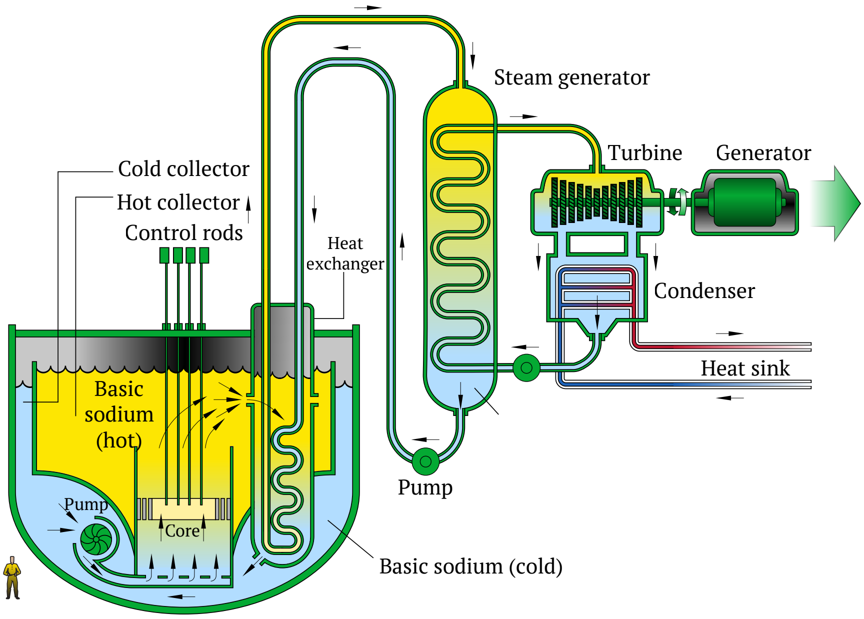

Figure 4. The concept of a nuclear power plant based on fast neutrons (SFR)

Source: R.M. Meyer *et al.* (2013), M. Wang *et al.* (2020)

Table 3. Key design parameters of the overall SFR concept

Reactor parameters	Unit of measurement	Reference value
Reactor power	MW	500-1000
Thermal efficiency	%	40-42
Coolant	-	Sodium
Melting temperature of the coolant		98
Boiling temperature of the coolant	°C	883
The maximum temperature of the coolant at the outlet	°C	530-550
Reference fuel composition	-	Metal alloy(oxide)
Facing	-	Ferritic with oxide particles

Source: R.M. Meyer *et al.* (2013)

Sodium, as a highly reactive metal, has the property of reacting with water, which leads to the release of hydrogen and heat. This reaction can cause spontaneous combustion when sodium comes into contact with water. In addition, at high temperatures, sodium can ignite in some conditions. Thus, the operation of reactors of this type requires taking special safety and caution measures. One such measure is the use of a three-flow circuit with an intermediate sodium loop between the reactor coolant system (primary sodium) and water, which acts as the working fluid in the power cycle.

Lead-cooled fast reactor, molten salt reactor and supercritical water-cooled reactor. LFR is a type of fast neutron reactor that uses lead as a coolant to transfer heat from nuclear reactions (Fig. 5). This technology uses lead for cooling and simultaneously shielding against radiation, which ensures stable and safe operation of the reactor. An alloy of lead and bismuth can also be used as a coolant. It operates at an outlet coolant temperature of approximately 550°C, but it can reach up to 800°C under atmospheric pressure. The primary fuel type for this reactor is nitride fuel, utilized for its optimal performance (Sargsyan *et al.*, 2023).

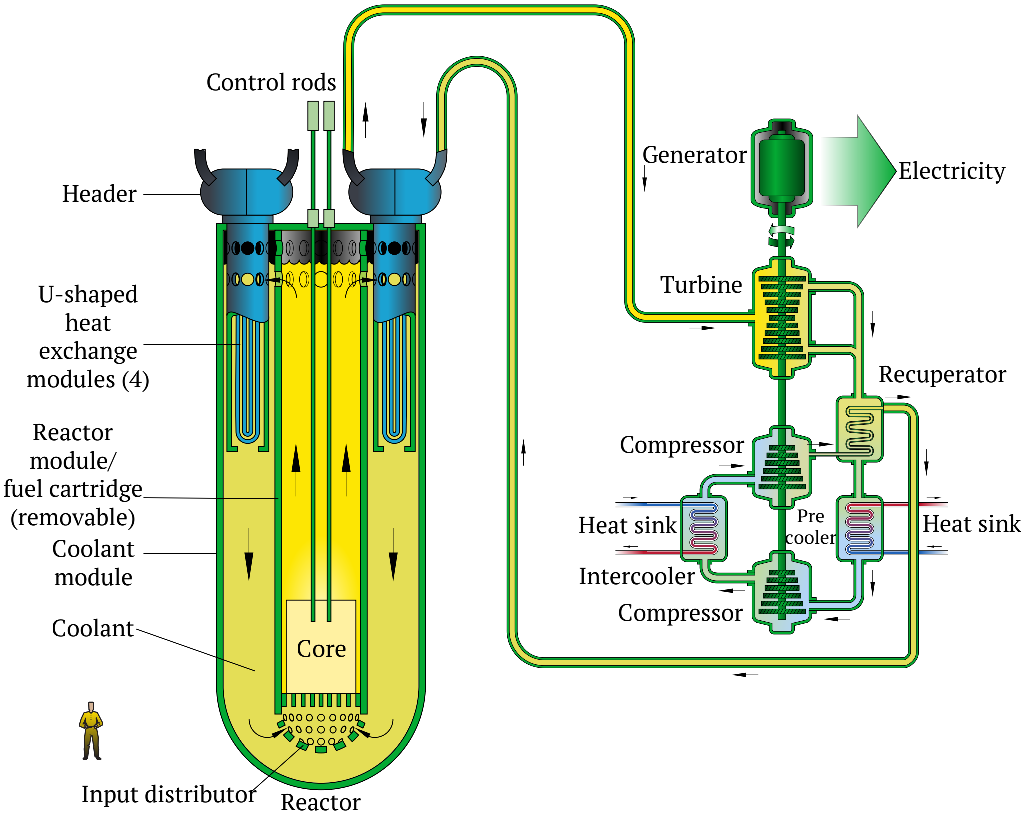

Figure 5. The concept of a nuclear power plant based on LFR

Source: M. Tarantino *et al.* (2021)

In the United States, for example, the supercritical carbon dioxide Brayton gas turbine cycle has been chosen as the primary for this type of reactor. At the same time, in some countries, the supercritical Rankine steam cycle is considered as the main option (Table 4). The difference in the choice of power cycle in different countries reflects the diversity of approaches in implementing technologies for LFR and emphasizes the importance of finding optimal solutions for its improvement and safety in various contexts.

Table 4. Main design parameters of LFR

Reactor parameters	Unit of measurement	Brest-300	Brest-1200
Thermal power	MW	700	2800
Electrical power	MW	300	1200
Thermal efficiency	%	43	
Melting temperature of the coolant	°C	328	
Boiling temperature of the coolant	°C	1743	
Coolant inlet temperature	°C	420	
Coolant outlet temperature	°C	540	
Mass consumption of the coolant	t/s	40	158
The maximum speed of the coolant	m/s	1.8	1.7
Fuel	-	Uranium nitride + plutonium nitride	
Fuel loading	t	16	64
Fuel residence time in the reactor	years	5	5-6
The maximum facing temperature	°C	650	
Temperature at the inlet/outlet of the steam generator	°C	340/520	
Power of the steam generator	t/s	0.43	1.72
The term of operation of the reactor	years	30	60

Source: I. Pioro & P. Kirillov (2013)

MSR is a thermal neutron facility that utilizes liquid fluoride salt with dissolved uranium, and graphite serves as the moderator. Upon introducing the fuel-salt mixture, the temperature at the inlet is approximately 565°C, but upon exiting the reactor, it can reach 700°C. Considering the option of hydrogen cogeneration, the temperature of the fuel-salt mixture at the outlet may even rise to 850°C. The efficiency of the facility, measured by the thermal efficiency, ranges from 45 to 50%. The installation scheme is detailed in Figure 6, and key parameters are provided in Table 5.

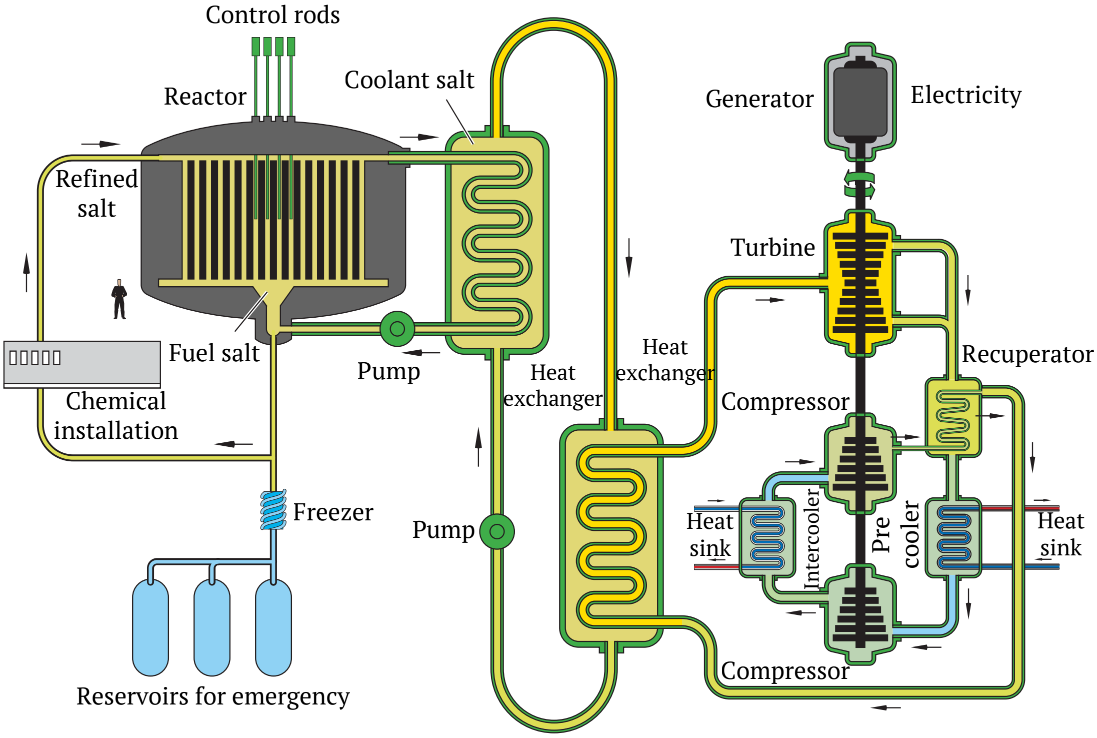

Figure 6. Concept of a nuclear power plant with a MSR

Source: M.P. Dion *et al.* (2020), V. Levchenko *et al.* (2023)

Table 5. Key design parameters of the MSR concept

Reactor parameter	Unit of measurement	Reference value
Reactor power	MW_{el}	1000
Net thermal efficiency	%	44-50
Average power density	MW_t/m^3	22
The temperature of the fuel-salt solution at the inlet/outlet	°C	565/700 (800)
Retarder	-	Graphite
Burner of the neutron spectrum	-	Thermoactinide

Source: M.P. Dion *et al.* (2020)

SCWR is considered an evolution of modern water-cooled nuclear reactor systems. In comparison to traditional nuclear reactors, the SCWR offers a new approach, utilizing water under supercritical pressure and high temperatures. The SCWR aims to surpass limitations PWR faced by achieving even higher pressures and temperatures (Krykova *et al.*, 2021).

In the case of BWR, steam is directly supplied from the nuclear reactor to the turbine. The SCWR, on the other hand, is designed to operate at supercritical pressure and high temperatures, enabling more efficient and optimal energy utilization. This technology employs the concept of nuclear superheating of steam, providing an outlet temperature exceeding the critical temperature but at a pressure lower than the critical pressure. Modern supercritical pressure turbines used in coal-fired power plants have demonstrated successful results for over fifty years, operating at pressures around 25 MPa and high inlet temperatures approaching 600°C. However, in the context of the SCWR, the use of water under supercritical conditions defines a new frontier of efficiency, potentially allowing for even more effective energy utilization and higher productivity (Novotny & Guzonas, 2020).

The classification of SCWR can be considered from various perspectives, such as the maximum pressure, neutron spectrum, and moderator material. One classification method based on maximum pressure divides PWR into two main categories: Pressurized Vessel (PV) and Pressurized Tube (PT) or Pressurized Channel (PCh). To ensure optimal operation of pressurized heavy-water underwater reactors, pressurized tubes of approximately 50 cm thickness are required, capable of withstanding supercritical pressure. The diagram of a nuclear power plant with a PV-type SCWR reactor is presented in Figure 7.

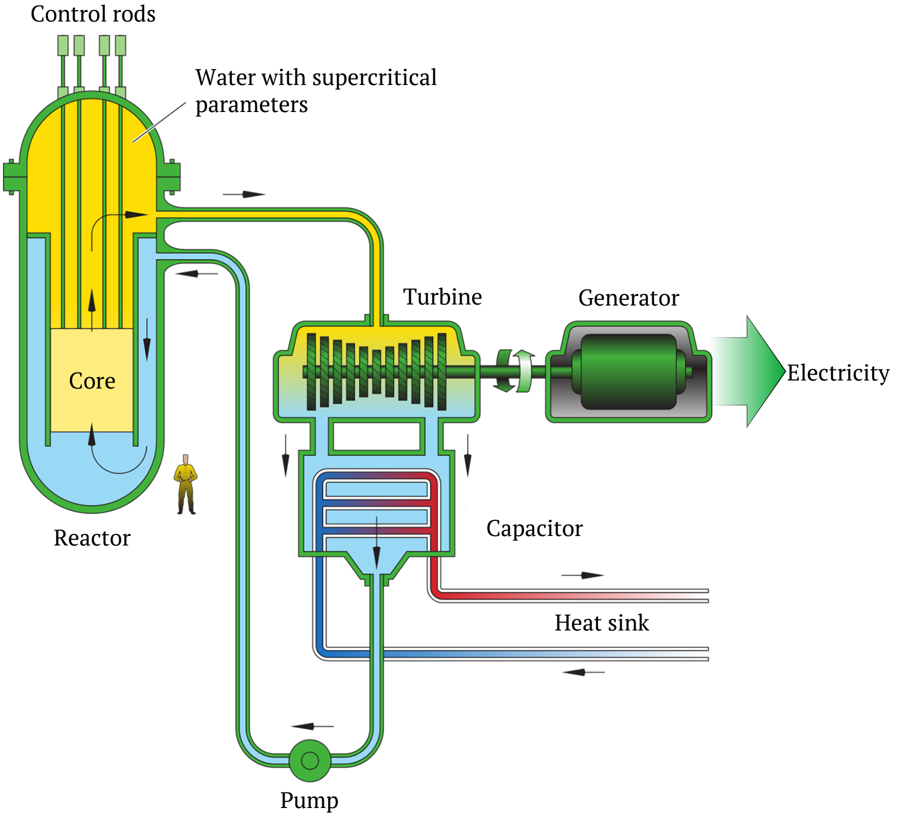

Figure 7. Concept of a nuclear power plant with a PV SCWR

Source: M. Krykova *et al.* (2021)

The active zone of reactors with pressurized tubes consists of channels with distributed pressure, which can be placed vertically (or horizontally). This approach is similar to the construction principles of reactors such as the Canada Deuterium Uranium (CANDU) and the High-Power Channel-type Reactor (HCCR or RBMK). For instance, the SCWR-CANDU reactor comprises 300 fuel channels that placed horizontally (Fig. 8). The option with a vertically oriented active zone should also not be ruled out (Fig. 9).

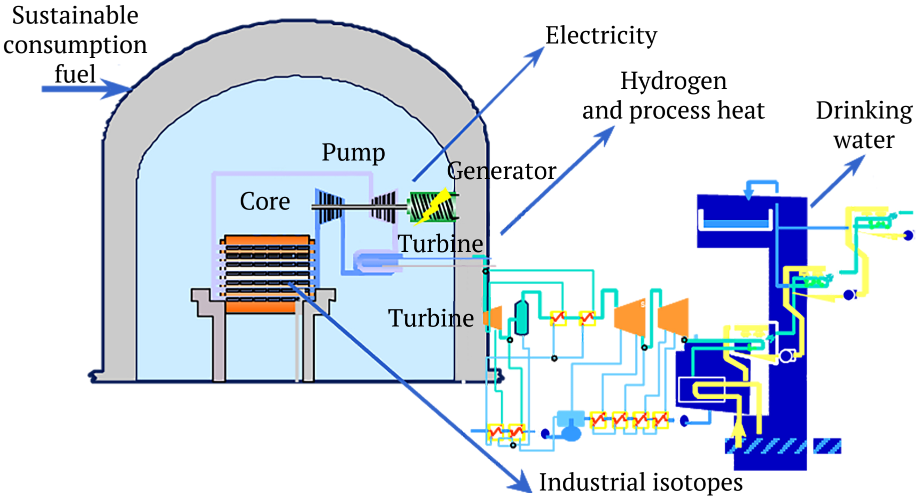

Figure 8. Concept of a nuclear power plant with a SCWR-CANDU type reactor with PT under pressure
Source: I. Pioro & P. Kirillov (2013)

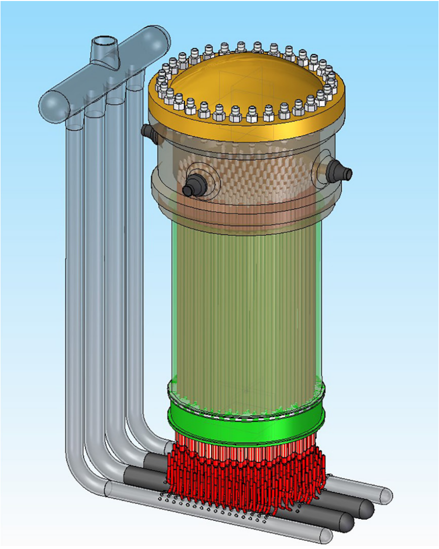

Figure 9. Variant of the vertical configuration of the active zone of the PT SCWR-CANDU reactor
Source: I. Pioro & P. Kirillov (2013)

The specifications of SCWR reactor designs indicate that the majority of these systems belong to the thermal neutron spectrum category. This means they operate in a neutron spectrum where thermal neutrons predominate, which is a typical choice for many modern SCWRs. However, variations also allow for the use of fast neutron spectrum designs, providing greater flexibility and diversity (Yamaji *et al.*, 2023). In SCWR designs with a thermal neutron spectrum, various types of moderators – liquid or solid – can be employed. Options include light or heavy water, graphite, among others. This diversity enables the exploration and implementation of various concepts, considering the specificity of each material and its interaction with the reactor's energy processes. A crucial aspect is that the concept of a liquid moderator can be applied in both pressurized and gas-water variations of the reactor, offering versatility in the operation of these systems.

In pressurized water reactors, the moderator and the coolant are isolated, creating many variations to select the optimal moderator depending on the specific needs of the reactor. The diversity of moderator options in pressurized water reactors creates a broad spectrum for experimentation and innovation in nuclear power, allowing for the exploration of different methods and approaches to improve the efficiency and safety of reactor installations.

Considering options for improving safety in PT SCWRs is the use of a liquid moderator, as this approach can have a number of advantages. This liquid moderator plays an important role in improving reactor safety and provides an additional layer of protection in emergency situations. However, significant drawbacks of this approach include increased heat losses resulting from heat transfers. This is relevant in SCWR systems, where high temperature and pressure present certain challenges in managing thermal processes and heat dissipation. These aspects require further research and technology refinement to mitigate the negative impact of increased heat losses and improve the efficiency of this reactor type (Ibrahim *et al.*, 2019).

It's worth noting that the use of a solid moderator is also a possibility. In RBMK, HTR, and other type reactors, graphite is currently used. This approach may have some peculiarities, as it is important to take into account that graphite can explode under certain conditions. Therefore, alternative variants are being considered as alternatives. The use of such materials can help reduce heat losses. However, it's essential to consider that these moderators do not provide a passive safety system that automatically reacts in emergency situations. While these materials have their advantages in terms of efficiency, they require systematic control and management to ensure the safety and efficiency of the reactor system.

In SCWR-type reactors, the high operating temperatures impose significant thermal loads on fuel elements. This is particularly relevant in Light Water Reactors (LWR) and Pressurized Heavy Water Reactors (PHWR), where uranium dioxide (UO_2) is used as the primary fuel. However, UO_2 has limited thermal conductivity, and overheating may occur in the central regions of the reactor core. Therefore, various alternative fuel types with higher thermal conductivity are being studied. One approach is the use of compounds such as UO_2-BeO, UO_2-SiC and others. The notable feature of these materials is their thermal conductivity properties, which can contribute to better heat distribution in the reactor system and prevent overheating (Peiman *et al.*, 2023).

The use of alternative fuel materials allows for temperature control in the reactor, minimizes the risks of overheating in areas with high heat flux, and ensures a more efficient operation of the reactor system.

DISCUSSION

Researching and analysing next-generation nuclear reactors is a crucial step in the development of modern nuclear energy. This underscores the need for efficient energy resource utilization and ensuring environmentally sustainable electricity production. Fourth-generation nuclear reactors represent a transition from old reactor models to new, innovative systems aimed at improving efficiency and safety. A detailed analysis of these reactors is essential for understanding their operation, efficiency, and environmental impact. Each reactor type is expected to increase the thermal efficiency, reduce the risk of accidents, and minimize radioactive releases. Research helps identify the advantages and disadvantages of each type and determines directions for further improvement. An important feature is that each type of nuclear reactor has unique characteristics defining its efficiency, safety, and environmental sustainability. Different technologies are used for energy production, with variations in heat conversion methods, construction materials, and nuclear process control. These differences determine not only reactor performance but also potential risks and opportunities for further development. Each reactor type requires a unique approach to management, waste storage, and safety measures, necessitating further scientific research and analysis for optimal nuclear facility functioning.

According to F. Osuský *et al.* (2020), a significant feature of gas-cooled reactors is their thermodynamic and thermophysical characteristics, ensuring highly efficient and safe nuclear facility operation. One key advantage of using gas is its resistance to ionizing radiation generated during nuclear reactions. This means that the reactor's gas system has high resilience to damage resulting from radiation exposure. Additionally, gas-cooled reactors may achieve higher efficiency compared to other types due to the gas's high heat transfer and mass exchange characteristics, enabling the conversion of nuclear reaction energy into useful electricity. The work by the researchers indicates the efficiency advantage of gas-cooled reactors, making them attractive for increasing nuclear energy productivity. This study further expands the knowledge presented by the authors by delving deeper into complex influences that can impact the choice of reactor type, providing a more comprehensive comparative analysis and additional crucial aspects to consider in selecting the optimal reactor type for specific conditions and needs.

According to M. Singh *et al.* (2022), a supercritical water-cooled reactor also has defining features and advantages, making it appealing in the field of nuclear energy. The use of water as a coolant reflects its high heat capacity, allowing effective heat dissipation from nuclear reactions. This makes it efficient in controlling the reactor's temperature. Safety is another notable advantage of such a reactor, as the research indicates its potential for high-speed heat removal even in the event of cooling system failure, making it less vulnerable to accidents. This study complements the conclusions mentioned earlier by providing a more in-depth understanding of various aspects compared to other types of nuclear reactors. Since this study reveals not only thermophysical and thermodynamic characteristics but also other aspects, this analysis allows for a broader spectrum of the impact of different reactor types on nuclear energy, facilitating a more thorough comparative analysis and providing additional important considerations when choosing the optimal reactor type for specific conditions and needs.

Research by Z. Zhao *et al.* (2022) reveals important aspects of a supercritical water-cooled reactor equipped with different types of moderators. Since moderators in reactors, such as graphite, beryllium, heavy water, or others, are key components in controlling nuclear reactions, the study emphasizes that using liquid moderators in supercritical water-cooled reactors has the potential to enhance nuclear technology. This improvement can result in efficient use of nuclear fuel and reduce the risks of accidents. The authors' research sheds light on the significance of various moderator types in supercritical water-cooled reactors. By examining liquid moderators like graphite, beryllium, heavy water, and others as crucial components for nuclear reaction control, the author identifies their importance in advancing nuclear technology. This approach may contribute to increased resource utilization efficiency in nuclear facilities and reduce environmental impact, promoting the adoption of safer and more stable technologies in nuclear energy.

According to S.A. Alameri & A.K. Alkaabi (2020), water-graphite reactors with supercritical coolant parameters represent an interesting direction in nuclear technology where water and graphite serve as key components for regulation and control of nuclear reactions. The researchers note that such reactors have the potential to provide high efficiency in nuclear fuel utilization. The combination of water and graphite allows achieving optimal reaction parameters, reducing losses of nuclear materials, and ensuring efficient energy utilization. Comparing the results of research by the authors with the present study, it is noteworthy that the latter examines various aspects of nuclear reactors, including not only water-graphite but also other reactor types. The study comprehensively analyses diverse technologies, materials, and constructions used in nuclear facilities to understand their advantages and limitations. This approach focuses on the specificity of water-graphite reactors with supercritical coolant parameters and their potential contribution to increasing the efficiency of nuclear fuel utilization. Simultaneously, this research aims to provide a general overview and comparison of different reactor types, considering their advantages and potential limitations in the context of efficiency and safety.

As per the research by Y. Wang *et al.* (2021), sodium-cooled reactors, despite several advantages, also present challenges and peculiarities requiring attention and management for optimizing their efficiency and safety. One primary characteristic is the chemical activity of sodium. Since sodium, used as a coolant, is highly chemically active, its interaction with water or air can create reactions with high energy and speed, posing a potential threat to reactor safety in case of accidents. The aspects mentioned in the researchers' research underscore the need for continuous work and improvement in sodium-cooled reactor technology. This highlights the importance of significant efforts in developing new technologies and control methods to ensure the safety and efficiency of such reactors. High attention to these aspects is necessary for continually reducing potential risks arising during operation and ensuring the reliability and stability of these systems.

Further research in the field of nuclear energy is crucial for the gradual development of this technology. It will allow a deeper understanding of various reactor types, their advantages, and limitations, contribute to the development of new control methods that enhance the safety and efficiency of nuclear energy utilization. Moreover, research can focus on reducing environmental impact and optimizing resource utilization, which are key aspects in the modern energy landscape. The development of new technologies and an in-depth understanding of nuclear facility principles play a vital role in ensuring sustainable and safe use of nuclear energy in the future.

CONCLUSIONS

Summarizing the results of the conducted research, it should be emphasized that the development of nuclear technologies is of great significance for the present and future energy landscape. Nuclear energy is considered a substantial source due to its potential to provide electricity over extended periods, even considering its non-renewability. However, it is important to bear in mind that modern nuclear power plants generate radioactive waste, requiring careful control and storage. In this context, fourth-generation reactors can not only reduce the amount of generated radioactive waste but also optimize fuel utilization and decrease the risks of accidents. Their key advantage lies in the use of advanced technologies allowing the processing of waste, reducing their radioactivity and storage duration. Additionally, new reactors may feature improved cooling systems and automated control mechanisms, enhancing their safety and reliability.

During this study, six main types of nuclear installations were thoroughly analysed, including: GFR (HTR), VHTR, SFR, LFR, MSR and SCWR. Among the critical aspects, the study also delved into various types of reactor cooling, analysing possibilities for reducing radioactive waste and addressing safety risks associated with nuclear installations. Furthermore, attention was given to exploring promising directions in the development of new reactors, aiming for more efficient nuclear fuel utilization and reduced radioactivity of waste. These aspects were investigated to identify key trends and opportunities for the further development of nuclear technologies to ensure a sustainable and secure energy future.

Major directions for further research into next-generation reactors may include the optimization of cooling systems to enhance heat exchange efficiency and ensure better temperature control, the development of monitoring systems for constant control of reactor parameters, and the improvement of emergency systems to minimize potential adverse consequences. Equally important is the advancement of methods for managing radioactive waste, including reduction and further processing. All these research directions have the potential to reshape the paradigm in nuclear energy, directing its development toward a more sustainable, secure, and efficient future.

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CONFLICT OF INTEREST

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Дослідження та аналіз ядерних реакторів нового покоління у світі

Анотація. Дослідження нових ядерних реакторів набуває невідкладного значення у світі через потребу постійного вдосконалення технологій для забезпечення безпеки, ефективності та зменшення викидів. Це важливо в контексті кліматичних змін і швидкого технологічного розвитку, що вимагають постійного оновлення й удосконалення ядерної енергетики. Метою роботи було проаналізувати реактори нового покоління у світі, а також визначити їхні переваги та можливі перспективи в майбутньому. Методами, що використовувалися під час дослідження, були статистичний метод, порівняльний метод, а також аналіз. Результати проведеного аналізу врахували сучасні технологічні та безпечні параметри, що стосуються роботи таких реакторів, зокрема їхню здатність до оптимізації використання палива, підвищення безпеки експлуатації, та ефективного управління радіоактивними відходами. В результаті роботи було проаналізовано ядерні реактори IV покоління, що включали в себе: реактор із швидкими нейтронами, що використовує газове охолодження; дуже високотемпературний реактор; реактор, де натрій використовується як теплоносій; реактор на швидких нейтронах зі свинцевим охолодженням; реактор, де реакція відбувається в розплавленій солі; та надкритичний водяний реактор. Кожен з цих реакторів має свої особливості, що роблять їх унікальними в своїй сфері застосування. Наприклад, реактори з газовим охолодженням мають високу продуктивність завдяки здатності досягати високих температур без значного тиску. В свою чергу реактори на розплавленій солі володіють гнучкістю у використанні різних видів палива, включаючи відпрацьоване, та можуть допомогти знизити рівень радіоактивних відходів завдяки використанню спеціальних матеріалів. В процесі аналізу було відзначено, що реактори IV покоління, використовуючи різні технології охолодження та сповільнення реакцій, позначаються високою ефективністю, низьким ризиком аварій та здатністю до виробництва стабільної електроенергії, а також вдосконалені методи контролю реакцій, відкривають нові можливості для ефективного виробництва електроенергії та підвищення безпеки в ядерній енергетиці. Практичне значення дослідження полягає в можливості удосконалення сучасних технологій виробництва електроенергії та забезпеченні більшої безпеки та ефективності у галузі ядерної енергетики

Ключові слова: атомна енергетика; генерація електроенергії; оптимізація використання палива; технології охолодження; сповільнювач; реакції