SECTION 6. ENERGY

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6.1 Digital doubles and intelligent technologies in the training of NPP operators

Nuclear power plants (NPPs) are extremely complex technological facilities that play a key role in the production of electricity. They use a controlled nuclear fission process to generate large amounts of energy converted into electricity. However, the complexity of the design, the interaction of numerous safety systems and the need for high-precision control of a nuclear reactor make nuclear power plants objects of increased risk. Any technical malfunction or operator error can lead to serious consequences, including accidents, leaks of radioactive materials and environmental disasters [144].

Due to the critical importance of safety in the operation of nuclear power plants, special attention is paid to the training of personnel. To do this, modern simulator complexes are used that simulate the real operating conditions of nuclear power plants. They allow the operator staff and engineering personnel to acquire the necessary skills in a safe environment, work out actions in pre-emergency situations and learn how to prevent the occurrence of potential accidents.

Modern training complexes should be based on advanced technologies, in particular on methods of mathematical modeling and digital doubles (Digital Twins). Thanks to these approaches, high-precision simulations of NPP operation are created, which take into account dynamic changes in the parameters of the nuclear reactor, cooling systems, power supply and other important components of the plant. The use of digital twins allows you to simulate different scenarios of the station, predict the development of events in case of deviations from the standard mode of operation, as well as test new technological solutions without risk for real technological equipment [145].

In addition, mathematical modeling allows the analysis of complex physical and technical processes occurring in the nuclear reactor and its auxiliary systems. This allows not only to improve NPP management methods, but also to improve the overall level of nuclear power safety.

Thus, the use of simulator systems, digital twins and mathematical models is an integral part of modern nuclear energy, aimed at ensuring maximum reliability and safety of NPP operation.

6.1.1. Digital doubles as a simulator tool

A digital twin is a virtual model of a physical system that uses real data to predict the behavior of an object. It allows you to create a detailed simulation of the operation of the NPP power unit, providing accurate visualization and analytics of all working processes [146]. The main stages of creating a digital twin simulator for nuclear power plants include:

✓ development of a mathematical model of the NPP power unit (determination of key physical and thermotechnical parameters, development of algorithms describing the behavior of heat exchange systems, coolant circulation and reactivity control, creation of hydrodynamic and thermodynamic models for assessing the state of the reactor and auxiliary systems);

✓ integration of data from sensors and control systems (using information from real sensors and SCADA systems to constantly update the model, using machine learning algorithms to analyze deviations from nominal parameters, adapting the digital twin to current operating conditions, which allows obtaining realistic learning scenarios);

✓ creation of interface for interaction of operators with simulator (development of graphical interface for visualization of main NPP systems; Integration of controls to simulate the real-time operation of operators inclusion of emergency scenarios for personnel training in emergency situations);

✓ implementation of training algorithms based on the obtained simulation data (analysis of operators' reactions to various operational situations and their assessment using artificial intelligence, adaptive adjustment of training programs based on user errors and successes, use of virtual and augmented reality (VR/AR) technologies to improve training efficiency).

6.1.2. Complex structural and functional diagram of interaction of digital twin with NPP operator

The interaction of the digital twin with the NPP operator includes several key components that ensure the continuous exchange of information between the physical object, control systems, artificial intelligence, analytical tools and external regulatory structures (fig. 1).

The physical power unit consists of a nuclear reactor, turbine, generator, cooling systems and other critical units. Its condition is continuously monitored using monitoring and monitoring systems such as SCADA and automated process control system, which receive data from sensors of temperature, pressure, power, radiation level and other parameters. These data are fed into a digital twin that performs mathematical modeling, analyzes the information received and predicts possible deviations in the operation of nuclear power plants [147].

The digital twin interacts not only with control systems, but also with analytical modules for predicting accidents, which assess the probability of pre-emergency situations and offer options for their avoidance. An important component is artificial intelligence, which analyzes structured archives in specialized automated process control system databases, identifies patterns and optimizes control algorithms. Thanks to this integration, the digital twin can provide the operator with detailed predictions of the state of the system, suggest corrective actions and automatically change certain parameters of the station to improve its efficiency.

The operator receives information in the form of visualized reports and analytical forecasts, which allows him to make informed decisions regarding the control of the power unit. If necessary, the operator can influence the NPP executive systems by adjusting the reactor power, changing the coolant circulation parameters or turning on additional safety mechanisms.

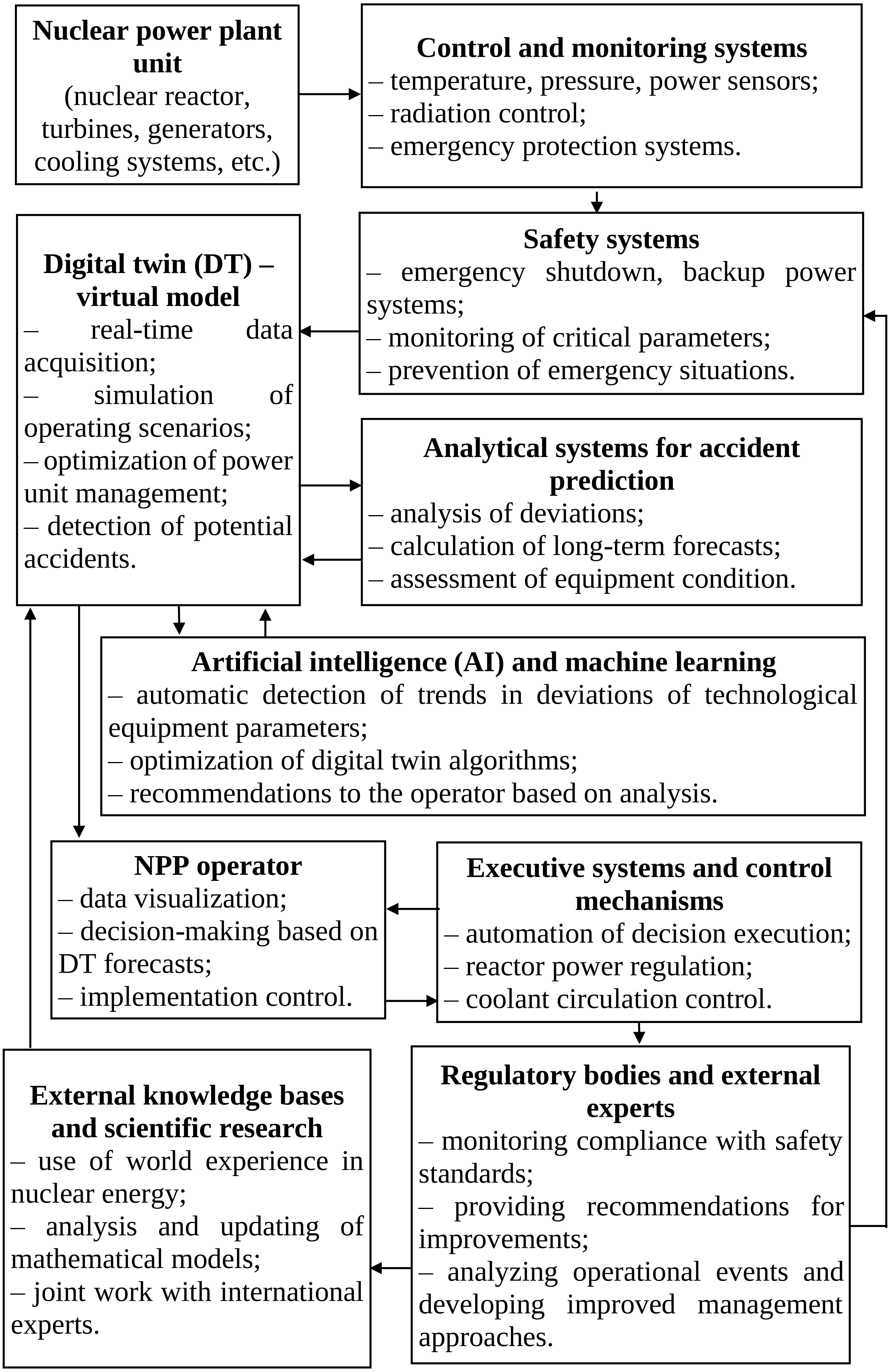

Figure 1. Complex structural and functional diagram of interaction of digital twin with NPP operator

In addition, the digital twin interacts with regulatory authorities that monitor the compliance of NPP operation with international safety standards, and external knowledge bases containing the most modern scientific research in the field of nuclear energy. This allows you to continuously improve the digital twin models and increase the efficiency of the station.

Thus, the digital twin acts as a key tool for improving the safety and efficiency of nuclear power plants, providing equipment failure prediction, control automation and support for operator decision-making. Its interaction with the physical power unit, analytical systems, artificial intelligence and regulatory authorities can significantly reduce the likelihood of accidents and optimize the operation of nuclear power plants.

6.1.3. Development of learning algorithm stages based on the obtained simulation data

Modern nuclear power plants require highly qualified operators, since their decisions can affect the safety and stability of the power unit. Artificial intelligence is used to assess personnel responses to various operational situations, which analyzes the actions of operators in real time or during training simulations. Such systems allow you to identify patterns in behavior, identify weaknesses in the decision-making process and predict the effectiveness of personnel in emergency situations [148].

Based on data on the interaction of the operator with control systems, time delays in reactions, the correctness of the execution of algorithms and decisions made, artificial intelligence forms an objective assessment of skills. This makes it possible to automatically adjust training programs, increasing the level of operator training and reducing the risk of errors during NPP operation.

Traditional methods of operator training often do not take into account the individual characteristics of each specialist, which is why the process of learning knowledge can be ineffective. The use of artificial intelligence and digital twins allows you to implement adaptive training programs that automatically change the complexity and content of training depending on the successes and mistakes of users.

Such systems analyze the results of tests, actions in simulations, the level of assimilation of theoretical material and the practical skills of operators. If a particular user demonstrates poor training in a particular area (e.g., control of reactor cooling systems), the curriculum automatically includes additional training on this aspect. On the contrary, if the operator quickly masters the material, the system can offer him more complex scenarios, which allows him to more effectively develop decision-making skills in emergency situations.

Thanks to this approach, training becomes personalized, which allows faster and better preparing staff for real working conditions.

The use of VR (virtual reality) and AR (augmented reality) significantly increases the efficiency of training of NPP operators, allowing them to work out various scenarios in the most realistic conditions without risk to real equipment. VR simulations allow operators to fully immerse themselves in the virtual environment of nuclear power plants, where they can learn to control systems, respond to emergencies and improve teamwork skills.

AR technologies, in turn, can be used to supplement the real working environment with digital prompts, interactive instructions or dashboards. For example, operators can get real-time visualization of equipment operation parameters, predicted scenarios or prompts for operations. The use of VR/AR in training programs can significantly improve the quality of personnel training, as operators not only learn theoretical aspects, but also acquire practical skills in a safe but realistic environment. This contributes to a better assimilation of the material, faster adaptation to working processes and a decrease in the probability of errors during the actual operation of nuclear power plants.

The developed training system for NPP operators is based on a personalized, dynamic approach that combines adaptive learning, VR/AR technologies, as well as big data analysis using artificial intelligence (fig. 2).

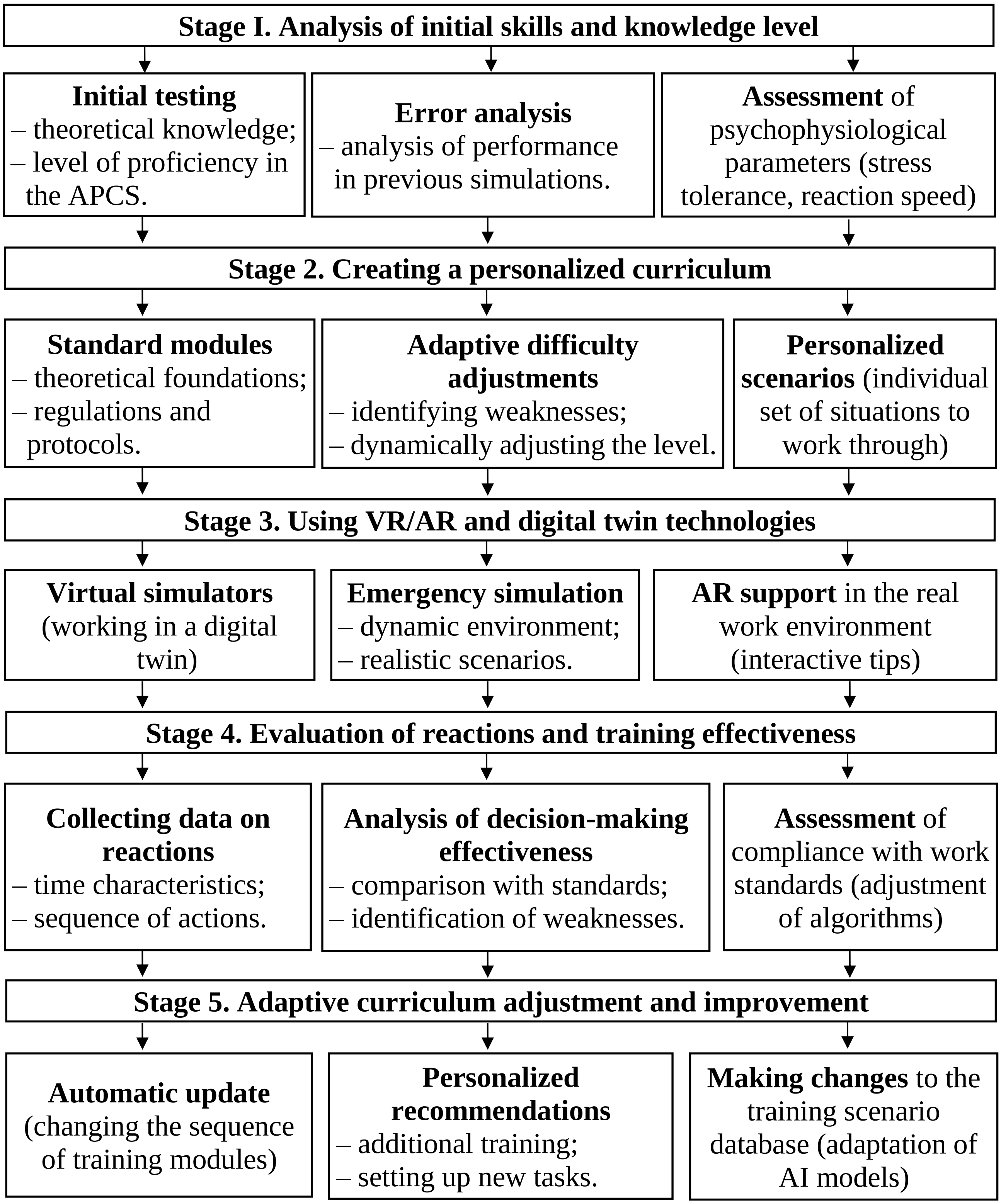

Figure 2. Structural and functional scheme of NPP operators training

This scheme is characterized by flexibility, an integrated approach to assessing knowledge and skills, as well as the possibility of continuous improvement of training algorithms.

Stage I. Analysis of initial skills and knowledge level. Before starting training, it is necessary to assess the level of training of the operator, to identify his strengths and weaknesses. Three main methods are used for this:

✓ preliminary testing - the level of theoretical knowledge about the operation of NPP, algorithms of actions in standard and emergency situations, understanding of the principles of operation of control systems (CAS APCS);

✓ error analysis - if the operator has already been trained or worked in the system, its preliminary results, typical errors and level of response to emergency situations are analyzed;

✓ assessment of psychophysiological parameters - the speed of reaction, resistance to stress, the ability to multitask and concentration of attention is determined.

The obtained data allow to form an individual profile of each operator and determine the optimal training strategy.

Stage 2. Creating a personalized curriculum. Based on the analysis of initial skills, an adaptive training program is created for each operator. It includes: standard modules (theoretical preparation, study of regulations, technical characteristics of equipment, standard operating procedures); adaptive difficulty correction (the machine learning algorithm determines the level of operator training and automatically adjusts the complexity of tasks: if the operator demonstrates high results, the system provides him with more complex scenarios, but if difficulties are found, additional training is offered); personalized scenarios - each operator is provided with a set of situations for testing corresponding to his level of training.

Stage 3. Using VR/AR and digital twin technologies. Realistic modeling is one of the key elements of modern training of NPP operators. Three main technologies are used for this:

– VR simulators - create a full-fledged virtual environment of nuclear power plants, in which operators can interact with equipment, work out standard and emergency scenarios without risk to real infrastructure;

– emergency simulation - the system creates dynamic scenarios simulating unpredictable events such as failure of cooling pumps, reactor temperature rise or power supply system failure;

– AR technologies are integrated into the real working environment, providing the operator with visual prompts for equipment operation, analytical data and recommendations in real time.

Stage 4. Evaluation of reactions and training effectiveness. After passing the training modules, the system analyzes the operator's reactions and determines how effectively he mastered the material. To do this, use the following methods:

– collecting data on operator reactions - the speed of decision-making, the sequence of actions, the accuracy of tasks in a virtual environment or real conditions are recorded;

– analysis of the effectiveness of decisions made - artificial intelligence compares the actions of the operator with normative algorithms and detects deviations;

– assessment of compliance with standards - the system analyzes whether the operator's decisions comply with NPP operation regulations and safety standards.

The results of the analysis allow you to determine how the operator is ready for work, as well as identify weaknesses that require additional training.

Stage 5. Adaptive curriculum adjustment and improvement. The curriculum is dynamic and changes according to the results of the operator. If problematic aspects are identified during the training effectiveness analysis, the system automatically changes the program by adding certain elements, such as:

– automatic updating of training modules - changing the sequence of classes, adding new scenarios for testing;

– personalized recommendations - the operator receives individual advice on improving skills and directions for further training;

– changes to the scenario database - the received training data are used to update the general scenario database and optimize the training system.

The proposed training system for NPP operators combines a personalized approach, the use of advanced digital modeling technologies and real-time reaction analysis. This allows not only to improve the quality of training, but also to minimize the risks of errors in real operating conditions. The use of VR/AR, digital twin and artificial intelligence makes the learning process as close as possible to the real operating conditions of nuclear power plants, which contributes to increasing the level of safety and efficiency of nuclear energy.

The introduction of digital twins, VR/AR technologies and artificial intelligence in the training of nuclear power plant operators is a key area for improving the safety and efficiency of nuclear power plants. The use of advanced simulation platforms allows personnel to work out both standard and emergency scenarios in a safe environment, which significantly reduces the risk of human errors in real conditions.

Thanks to digital twins, it is possible to create high-precision mathematical models of the operation of a nuclear reactor, cooling systems and power supply, which allows predicting possible equipment failures, optimizing control processes and improving training programs. The integration of these technologies with artificial intelligence makes it possible to automatically analyze the reactions of operators, adapt training programs based on their successes and mistakes and provide a personalized approach to training.

The developed training methodology includes the stages of initial assessment of operator skills, the formation of a personalized curriculum, the use of VR/AR simulations, the evaluation of reactions and adaptive adjustment of the program. This approach allows to provide comprehensive and effective training of NPP operators, which meets the modern safety and reliability requirements of nuclear energy.

Thus, digital twins and modeling technologies are an integral part of the modernization of the NPP personnel training system, contributing to increasing the level of safety, reliability and efficiency of nuclear power plants.