Immersive technology for training and professional development of nuclear power plants personnel

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Abstract

Training and professional development of nuclear power plant personnel are essential components of the atomic energy industry's successful performance. The rapid growth of virtual reality (VR) and augmented reality (AR) technologies allowed to expand their scope and caused the need for various studies and experiments in terms of their application and effectiveness. Therefore, this publication studies the peculiarities of the application of VR and AR technologies for the training and professional development of personnel of nuclear power plants. The research and experiments on various aspects of VR and AR applications for specialists' training in multiple fields have recently started. The analysis of international experience regarding the technologies application has shown that powerful companies and large companies have long used VR and AR in the industries they function. The paper analyzes the examples and trends of the application of VR technologies for nuclear power plants. It is determined that VR and AR's economic efficiency for atomic power plants is achieved by eliminating design errors before starting the construction phase; reducing the cost and time expenditures for staff travel and staff training; increasing industrial safety, and increasing management efficiency. VR and AR technologies for nuclear power plants are successfully used in the following areas: modeling various atomic energy processes; construction of nuclear power plants; staff training and development; operation, repair, and maintenance of nuclear power plant equipment; presentation of activities and equipment. Peculiarities of application of VR and AR technologies for training of future specialists and advanced training of nuclear power plant personnel are analyzed. Staff training and professional development using VR and AR technologies take place in close to real-world conditions that are safe for participants and equipment. Applying VR and AR at nuclear power plants can increase efficiency: to work out the order of actions in the emergency mode; to optimize the temporary cost of urgent repairs; to test of dismantling/installation of elements of the equipment; to identify weaknesses in the work of individual pieces of equipment and the working complex as a whole. The trends in the application of VR and AR technologies for the popularization of professions in nuclear energy among children and youth are outlined. Due to VR and AR technologies, the issues of "nuclear energy safety" have gained new importance both for the personnel of nuclear power plants and for the training of future specialists in the energy sector. Using VR and AR to acquaint children and young people with atomic energy in a playful way, it becomes possible to inform about the peculiarities of the nuclear industry's functioning and increase industry professions' prestige.

Keywords
virtual nuclear power plant, virtual reality, augmented reality, specialist training, professional development, popularization of professions

1. Introduction

Despite the rapid development of alternative energy sources, nuclear energy remains a powerful source of electricity generation. Currently, Ukraine has a developed atomic energy industry, based on four operating nuclear power plants (NPPs): Zaporizhzhia, Khmelnytsky, Rivne, and South Ukraine, and for the next decades, according to the "Energy Strategy of Ukraine till 2035" [1] it is planned only to increase the capacity of this industry. NPPs are high-risk facilities, and their development prospects are closely related to their safe operation and protection of territories, civilians, and the environment on the site. Under various adverse circumstances (violation of technological processes, safety, and operating conditions, technological accidents and incidents, natural phenomena, terrorism and sabotage, military operation, etc.), various emergencies may occur at NPPs that pose a significant risk to the environment, health of staff and the population of the surrounding areas. Analysis of technological accidents by the threat to human life, by nature of the action, by the scale of destruction of buildings, by the amount of material and economic damage, etc., shows that the most dangerous are the accidents that cause radioactive and chemical contamination of the environment [2].

We agree with the publication [3], stating that although nuclear energy has created a new round in the history of human development, three large-scale nuclear accidents (Three Mile Island, Chernobyl, Fukushima Daiichi) caused global change leading to significant radioactive

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contamination, damage of natural and agro-ecological systems and public health. Therefore, safety is a necessary condition for the development of nuclear energy [2, 3].

In the new technological era, the digital state is becoming a normal state of functioning and developing many systems, areas, organizations, industries, and economies. Digitalization's primary purpose is to achieve the digital transformation of existing and creation of new sectors of the economy and modify spheres of life into new, more efficient, and modern ones [4]. High-tech production and modernization of industry with the help of digital technologies, the scale, and pace of digital transformations should become a priority of economic development [5]. In nuclear energy, digital technologies and successful projects, both foreign and domestic, need to be widely implemented.

Digital technologies are inevitably used in large industries and enterprises, and therefore staff training needs constant improvement. VR and AR technologies are an ideal tool for learning in the digital age. Because they are functional, accessible, it is possible to model complex situations that require adaptive thinking and specific skills. VR and AR technologies are already becoming the basis of training in an industrial environment as such activity becomes more effective and safer. The spread of immersion technology requires collaboration between industrial companies and VR and AR developers, ensuring that they meet various organizations' training and safety requirements [6].

The development and implementation of digital tools in energy companies and staff training are investigated in [3, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. Peculiarities of the functioning of potentially dangerous objects are described in [2, 20, 21, 22, 23, 24, 25, 26, 27]. Various aspects of the application of VR and AR technologies for training are investigated in publications [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56]. As VR and AR technologies are continually evolving, there is a need to continue research into applying these technologies to NPP personnel's training and education and promoting nuclear energy professions among children and young people.

The **purpose** of the study is to analyze the features and best practices of using VR and AR technologies to improve NPP personnel's skills and promote the profession in nuclear energy.

2. Research results

2.1. Application of VR and AR technologies for educational purposes

The new evolutionary stage of society's development is called the technological era requiring the training of specialists who will be competitive and able to master the professions of the future. We believe that the use of digital technologies, particularly VR and AR, is essential in the training of specialists in the new technological era [45].

We will analyze research within the framework of applying VR and AR technologies to train future professionals and improve their skills.

The digital transformation of society has led to the need for future professionals to quickly adapt to changing activities, apply digital technology, and continuously improve their competence. At present, in particular AR, various technologies can be used to support employees in different industries in the formation of the necessary competencies [57]. The potential of AR as an innovative learning environment that can be applied to other cases is also revealed. It is outlined what teaching and learning goals can be achieved using AR technology in teaching [36].

The analysis of scientific publications on the use of AR technology to support education, science, engineering, and mathematics was performed in the study of Ibáñez and Delgado-Kloos [35]. It is concluded that most AR applications for STEM learning offer research simulation activities. The considered programs offered several similar functions based on mechanisms of digital detection of knowledge for the consumption of information due to interaction with digital elements; most studies have evaluated the effect of AR technology on student learning outcomes; there are few studies with recommendations to help students carry out educational activities [35].

In [30] the tendencies of scientific publications for the last years are considered. The conducted analysis of bibliometric descriptions of articles related to the use of AR for educational purposes allowed us to conclude that mobile applications and paper-based materials with markers are the most convenient type of materials for AR, as they are easy to use and develop.

Syrovatskyi et al. [28] performed the historical and technological analysis of the experience of using AR tools for the development of interactive learning materials, characterized the software for designing AR tools for educational purposes, and identify technical requirements for the elective course "Development of virtual and augmented reality software".

Yuen et al. [47] provides a classification of mobile applications with AR technology in education. The following options are described: books with AR technology, which form a bridge between the physical and digital world; educational games; educational programs; object modeling; applications for skills training.

The prospects of AR technologies and their use as components of the cloud environment are described in [29, 58]. AR technologies for education require the development of new methodologies, didactic materials, and curriculum updates [59]. The main aspects of using AR in the learning process are designing a flexible environment; adjustment of educational content for mastering the material provided by the curriculum; development of research methods that can be used in teaching together with the elements of AR; development of adaptive materials, etc. The researches [28, 60] concluded and emphasized that at the current stage of development of digital technologies, it is advisable to share Unity environment for visual design, Visual Studio or similar programming environment, as well as the platforms of virtual (Google VR, etc.) and augmented (Vuforia or similar) reality.

The application of AR technologies in higher education and the obtained results are described in the [32, 61]. AR technologies are widely used in higher education to visualize a design model or for the modeling process. Considering that many students have difficulty understanding the mechanical systems, starting with a two-dimensional design plan, the use of AR technologies is promising. AR can answer the problem of establishing a connection between the representation and the real system. The AR scenario is implemented on an electromechanical mechanism. This makes it possible to identify components and their location and study the mechanism and, thus, more comfortable identifying, for example, the kinematic circuit or the flow of power transmission. The experiment results with students of technical specialties showed that students who used AR technologies had better learning outcomes.

The peculiarities of applying AR technology in technical universities are described in the [48, 62]. Thus, the introduction of AR technology in technical universities' educational process increases learning efficiency, improves the quality of knowledge acquisition, promotes students' learning and cognitive activity, and directs future professional research skills and competencies. Uriel et al. [49] also described how VR and AR technologies improve understanding of technical disciplines. One of the most critical problems in the first years of study in technical specialties is students' knowledge of basic scientific concepts. The study aimed to develop, design, and test VR and AR applications to improve basic scientific concepts for first-year students in technical universities.

2.2. VR and AR technologies application examples and trends in various industries

Industrial VR and AR is one of the critical concepts of industrial digitalization, which connects workers with the physical world through digital information. Figure 1 shows the VR application for industry. The AR market is expanding, but industrial implementation is still low. Large industrial companies seek to use AR, but they rarely use these technologies due to a lack of understanding of success factors. The study [13] identified the most crucial success factors and problems for implementing AR-based projects based on experiments. It is established that, although technological aspects are essential, organizational issues are more relevant for industry, which has not been described in detail in the scientific literature.

Figure 1: Example of application of VR for industry (https://www.tssonline.ru/).

Fauville et al. [14] describes the use of VR to raise awareness of climate change. At present, environmental literacy is essential for understanding threats such as global climate change. Most people do not understand the relationship between individual actions and their consequences for the environment, so VR technology can be a promising tool to solve these problems. Scientific publications devoted to the use of VR for the formation of ecological literacy of the population are considered.

AR technologies combine real-world images with virtual information such as 3D models or sounds. The use of AR technologies to solve various archeology problems and present tourists with ancient cultural heritage sites is described in the study [15]. As far as the AR technology is implemented using mobile phones, tablets, or smart glasses, tourist groups can examine ancient objects in the form they were in the past. The study aimed to improve video images obtained by drones to create 3D models of Roman baths, an important cultural heritage site in Turkey. To do this, two different tracking techniques were introduced: GPS-based drone tracking and monocular camera-based tracking.

The research [63] presents various examples of the application of VR in power engineering. In Scotland, there is a VR laboratory for the training of wind farm personnel. This laboratory was created to improve the training system and professional development of personnel to work with offshore wind turbines. The laboratory focuses on virtual projections of real installations. It developed the facility's digital model so that local college students could get a detailed understanding of maintenance, diagnostics of malfunctions, and repair of the turbine. Classes are held in the VR laboratory, which uses a particular visualization system: the user sees their own hands and feet simultaneously with the generator's three-dimensional image. The physical movements are correlated with the virtual world. That is, students and staff undergoing internships can inspect the turbine using a simulation. You do not need to go to the sea. In such conditions, risks are reduced, and there is an opportunity to practice skills and train [63].

Also, a significant reduction in costs should be considered when applying virtual simulators instead of training using existing equipment. Wearing of equipment is minimized, risks of early/emergency failure of separate elements of a working complex are excluded. Thus, it is possible to reduce costs due to the absence of the need to spend money on expensive components and providing trips to remote practical facilities [63]. Additionally, VR technologies can be used in exhibition stands to create high-quality visualization of projects. For example, at exhibitions, visitors to the MHI Vestas booth before watching a movie about a wind generator are given branded climbing equipment: a helmet, seat belt, and safety vest to enhance the sense of the reality of what is happening [64].

2.3. VR and AR technologies application examples and trends for NPPs

Following the Fukushima Daiichi nuclear accident, the NURESAFE7 simulation platform was created based on the NURSIM platform for safety analysis, operation, and nuclear reactor design. Virtual Nuclear Power Plant (Virtual4DS) is an integrated simulation platform (figure 2) that covers the NPP environment, which is based on a digital reactor, information and data (provided by the digital society), consisting of digital traffic, digital meteorology, and data about earth's crust processes. Based on big data, mobile Internet, artificial intelligence, cloud computing, the platform, and other advanced digital technologies make it possible to perform simulations of multi-active operations, consider the evolution of nuclear accidents, use to support management decisions, anticipate emergencies, etc. [3].

Qin et al. [16] stated that the design, manufacture, assembly, operation, and decommissioning of nuclear devices are complex processes. VR technology can be used at all stages to save time and reduce costs. VR technology and its characteristics are described. The China Fusion Engineering Test Reactor (CFETR) is in the engineering design stage, but a significant analysis is needed to ensure it is safe. This includes the study of plasma physical dimensions, stability, exfoliating layer, discharge process, and engineering analysis of its electromagnetic, thermodynamic, and structural characteristics. Many software applications are used simultaneously, which generates a large amount of data, so you need a system that can manage such a large amount of data. VR technology certainly meets this requirement. The configuration of the CFETR VR platform (both

Figure 2: Virtual nuclear power plant [65].

hardware and software) is studied, and the further development of this platform is described [16].

Gabcan et al. [17] described a 3D simulation model of water infiltration for radioactive waste in VR. A virtual environment scenario was created for the radioactive waste infiltration model applied to the Abadia de Goiás repository (Brazil). The study aimed to introduce a three-dimensional 3D simulation model of the repository. With the help of VR technology, they sought to improve water infiltration inside the reservoir by pre-numerical simulations. The underground storage is presented in three different ways. It compares the variation of the amount of radioactive material in the water penetration scenario as a function of color change in the 3D simulation model. Visual modeling, obtained by changing the color shade and opacity, together with the difference in the height of the infiltrated liquid creates a physical perception of the probable scenario of risk. Thus, the virtual reality environment model has the advantage that it allows perceiving the corresponding overall results of penetration [17].

It is essential to use VR and AR technology to model an NPP construction project and a detailed presentation of various aspects of such a project. The study provides a brief overview of the latest technologies VR, AR in the design and construction industry; a summary of various methods and software used to convert the Building Information Model into VR, AR, etc.; a comprehensive review of the application of AR to effectively address multiple issues of construction project management. The roadmap for the introduction of AR technologies for the construction of AEC is presented [18].

The research [66] stated that at the beginning of 2020, the software and hardware complex

“Virtual Digital NPP with WWER reactor” was put into commercial operation. The Virtual Digital NPP’s key features are the following: it is possible to carry out calculations using the compact Russian-manufactured supercomputer. It is possible to model and test any modes of operation of power units with the WWER reactor (water-water energetic reactor) – from regular operation to complex abnormal situations as well as to change the mode of operation and predict changes in the state of the equipment without any consequences, which, in turn, allows to make existing NPPs safer at all stages of the life cycle. The platform of the software and hardware complex of the “Virtual Digital NPP” will be the core of modern simulators development for the NPP’s operational staff, which will positively affect the quality of personnel training and operational safety station. “Virtual Digital NPP” is the primary step towards creating full-featured “digital twins” of NPP power units, as the calculation modules are combined into a single system. On its basis, it is possible to build detailed models of NPP power units. Besides, more than ten calculation modules were developed and verified for modeling a wide range of processes and phenomena occurring in the NPP power unit’s equipment. Practical application should begin in 2020. Based on the complex, the development of the scenario of emergency training at the NPP is organized. It is planned to use the complex to analyze projects for the modernization of existing NPP power units [66].

The software and hardware complex “Virtual Digital NPP” (figure 3) in 2019 passed more than 100 independent and comprehensive tests. Experimental operation of the complex confirmed the possibility of using the complex for emergency drills and extensive emergency exercises, verification of control algorithms for NPP power units, confirmation of emergency instructions, and design decisions of the most reliable equipment. The basis for the creation of “Virtual Digital NPP” was the long-term experience (in the field of creating simulators and modeling of processes at NPP power units) of the All-Russian Research Institute for Nuclear Power Plants Operation [66].

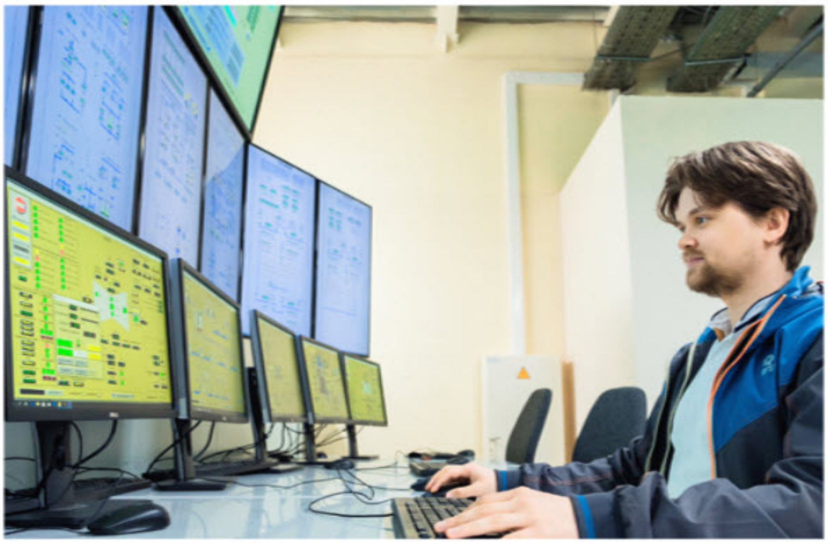

Figure 3: The software and hardware complex “Virtual Digital NPP” [66].

The work [67] states that the software and hardware complex "Virtual Digital NPP" is an essential technology for Belarus because Belarusian NPP is being built within this project's framework. This "Virtual Digital NPP" differs from foreign counterparts by a deeper degree of detail in the modeling of thermophysical processes that can occur at a real station, as well as relevant systems and equipment. The most crucial task of any nuclear power plant from the point of view of safety is to prevent the initiation and development of the processes that can lead to emergencies. Therefore, the virtual power unit can show how the real object's security systems will respond with maximum accuracy to regular operation disruptions, emergency processes, including those caused by malfunctions of NPP equipment. Moreover, in contrast to the simulators used for teaching and training personnel, the processes at the virtual NPP are demonstrated with the maximum possible approximation to the natural laws of physics. The virtual station screens show all the devices provided by the design of the entire block control panel of the NPP, so there are many options for situations modeling [67, 68].

Besides, creating a virtual power unit made it possible to conduct experiments in cyberspace, which is not cheap. One of the advantages of a virtual NPP is the ability to model large-scale equipment, with which experiments in real conditions are not possible. However, a complete refusal to conduct field experiments is impossible for the following reasons: 1) running experimental confirmation of newly created equipment and systems are one of the requirements of regulatory documents; 2) experiments should be performed at a high technical level to replenish the verification base, which allows improving the "Virtual Digital NPP". The use of a wide range of capabilities of "Virtual Digital NPP" allows not only to reduce the number of possible inconsistencies in the NPP design and check the interaction of systems during operation of the plant equipment in different modes before commissioning. As a result, it became possible to avoid expensive alterations and unjustified upgrades. Moreover, possible modernization of NPP power units during operation can now be checked first by a virtual power unit (figure 4), and only after receiving a positive result, implement it on real equipment [67].

Figure 4: Virtual power unit [67].

Currently, creating a virtual copy of a nuclear power plant ("digital twin") is a difficult task that needs to be addressed in several aspects: creating a virtual 3D model; creating the simulators that will be a basis of a virtual model; introduction of product lifecycle management for centralization and organization of data. For a true digital twin to exist, a virtual model must be very accurate and include even the smallest components. Because NPPs have a life cycle of 60 to 70 years, operators must ensure the digital twin's long-term reliability and viability. The digital twin combines several simulation tools, often created by different subcontractors. A successful digital twin would mean that all of these tools could be standardized to ensure compatibility [69].

In 2019, the GEMINA program was introduced, promoting research efforts using artificial intelligence and improved modeling tools to provide more flexibility in nuclear reactor systems, greater autonomy in operation, and faster iteration of the project. GEMINA has also set itself the ambitious goal of helping nuclear reactor developers reduce operating costs by ten times, mainly through predictive maintenance and model-based troubleshooting. GEMINA projects will focus on solutions for the reactor core's care and operation, plant balance, or the entire reactor system [70].

Various projects for the development of "digital NPP twins" are described in [70]. The projects for which funding is allocated envisage: 1) the result of a digital copy of a high-temperature reactor with fluoride salt cooling; 2) the digital copies should provide continuous monitoring, early warning, diagnosis and forecasting of emergencies, etc.; 3) the assessment of potential risks, hazard analysis and safety and maintenance assessment to identify areas for optimizing the operation of NPPs; 4) the development of a multidisciplinary 3D model, which in combination with VR will test methods that optimize service and security; 5) provide a virtual test environment for demonstration/modeling of operations and maintenance strategies of nuclear reactors; 6) the digital copies will simulate a passive cooling system with internal thermal-hydraulic faults and a typical cooling circuit with different operating modes and control states [70].

The French companies operating in the nuclear industry have launched the Reacteur numerique project. This project aims to develop a "digital reactor" that can be used starting from design to decommissioning of nuclear power plants. Among the expected results of the project until 2023, there are two innovative products. The first is a digital reactor for instructor training, reflecting the unit's physical phenomena and simulating various operational strategies. The instructors will use a web interface instead of a full-scale simulator. Instead of describing each system in detail, the model will reflect the installation's operation as a whole. The second innovation is an improved simulation service platform for educational purposes, covering the entire life cycle: design, commissioning, operation, maintenance, and even deconstruction. The platform will facilitate a range of research, covering everything from routine operations to significant accidents. Training of NPP personnel should become more efficient, and staff training costs will be reduced [71].

The publication [72] concluded that currently, VR and AR technologies for nuclear energy are used in the following areas (figure 5): modeling of various atomic energy processes; operation, repair, and maintenance of NPP equipment, presentation of activities, NPP construction; staff training and education.

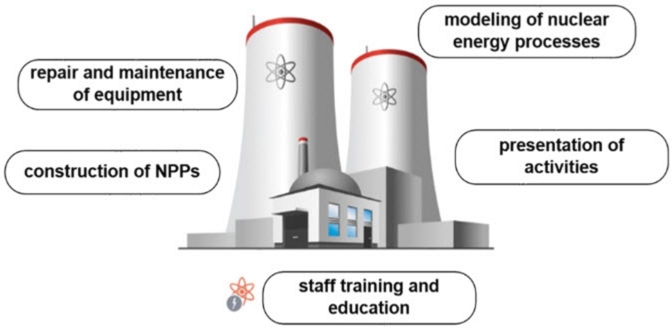

Figure 5: Areas of application of VR and AR technology for nuclear energy.

2.4. Peculiarities of application of VR and AR technologies for training of future specialists and advanced training of NPP personnel

NPPs are the object of critical infrastructure, so their reliability and safety, hence the personnel training, are subject to the highest requirements. VR technologies allow organizing such activity in the conditions close to real, and it is safe for participants and the equipment. VR technologies create the illusion of being inside a virtual environment and are cheaper than traditional learning equipment, and benefit from accessibility and ease of use [64]. VR is a handy tool that allows simulating any situation. With the help of VR, it is possible to test the security system and reproduce any regular processes to train employees and identify weaknesses in the work of individual elements of equipment and the work complex as a whole [63].

Reliable training is essential to ensure the operation of NPPs, which is the key to safe and productive activities. The cost of the slightest mistake in the energy sector can be incredibly high. To minimize such risks, special attention should be paid to training. The theory is essential, but it is nothing without good practice. VR systems are an effective simulator with which you can easily design any situation and work out a procedure to solve all possible problems. With the help of VR technologies, it is possible to 1) work out the procedure in an emergency mode; 2) work out the dismantling/installation of equipment elements; 3) optimize temporary costs for urgent repairs, etc. With the help of VR, you can visualize the project for collective acquaintance, further adjustment, and joint decision-making in the framework of corporate activities [63].

Kutsan et al. [46] substantiates the importance of using modern digital technologies to improve energy professionals' skills, including operational and dispatching personnel. The study justifies the need for the educational and methodological base, structure, and functions of the virtual research and training center for staff training in Ukraine's energy sector, including knowledge control, training, and critical competencies. The advantages of using a distributed environment for the organization of training and coaching of operational personnel with the help of modeling modes of operation of power systems in the virtual center are considered. To improve the skills of personnel in Ukraine's energy sector, virtual research and training center was designed, developed, and implemented, and its scientific support was provided. Besides, a full-featured mode web simulator has been developed and implemented.

One of the main tasks of simulation-based training is to reduce the time spent on competencies, to transfer high-level skills to each employee with maximum efficiency. With VR's help, employees are immersed in the epicenter of events to obtain the necessary equipment management and maintenance. VR technology provides benefits both for the study of a single sample of equipment and for the entire enterprise, especially using highly realistic three-dimensional process simulation. The same 3D models can be used in different scenarios, depending on additional learning requirements [6]. Interactive 3D applications allow you to organize training for remote or dangerous objects. A 3D model of the NPP unit eliminates the need to visit the facility for training: you can train in the office; the staff will not only be able to virtually explore the facility but also together with the instructor to play different scenarios [73].

A realistic and detailed VR learning environment helps to get to know the company and its work well before students appear to live for the first time. 3D graphics and sound give users a complete sense of immersion in the virtual world. Digital simulation devices and VR technology provide a similar gaming experience (this attracts the younger generation) and allow better assimilation of information [6].

The research [6] states that VR technologies are well suited for learning, as they provide immersion, better memory, and are cost-effective. The main advantage of simulation-based education is that the learning process is implemented in a continuous or long-repeated manner with the enterprise and students' security. Industrial enterprises are dangerous environments, and they are under constant exploitation. This fact dramatically complicates the organization of training with real equipment, especially when preparing for emergencies. Better-trained workers help reduce accidents, accident costs, and downtime. Investing in immersion training systems at an early stage of the equipment life cycle can maximize investment return [6].

The Nuclear Maintenance Applications Center, part of the American Electric Power Research Institute, has released an interactive manual with a VR interface for working with the Terry Turbine (figure 6). After wearing the connected VR helmet and running the program, the user enters the learning environment having four modes available [64]:

1) instruction – an animated video is launched, which shows the procedure for disassembly and assembly of the turbine line;
2) arbitrary – you can pull out and put back in place the nodes of the turbine in any order;
3) workshop – a user disassembles and assembles the unit with the help of prompts, the program alternately highlights the nodes;
4) test – only text instructions are available.

Besides, a pair of manual manipulators is used to control actions with a virtual turbocharger. Experts from the Electric Power Research Institute first tested the program. The energy company Dominion Energy received this simulator, tested it at three of its NPPs, and gave a high rating. A virtual simulator, which is more straightforward, cheaper, safer, and more interesting than the traditional one, should interest young people in working at nuclear power plants and improve personnel situation [64].

Using VR technologies for NPP construction, it is possible to control (support) the station's structure, perform staff training, present the construction project, and new equipment. For staff training, the VR complex includes a system of interactive interaction (tracking), which monitors

Figure 6: An example of the Terry Turbine simulator (https://www.youtube.com/watch?v=cCdlrxKHvk4).

the movement of a person dressed in a particular suit. Special VR-gloves allow users to work out the installation processes on virtual objects, check the level of assembly of structures, and the interchangeability of their parts [64].

Various specialized firms and organizations currently develop training equipment for nuclear power plants and other enterprises in the energy sector. One of them is NPP "Educational Technology" [74] (figure 7), which is a research and production enterprise with extensive experience in the development and production of components of modern high-tech educational environments for various sectors of industry. Educational equipment for nuclear energy, together with digital technologies, is designed to comprehensively support all forms of the educational process in the following specialties "Nuclear power plants: design, operation and engineering", "Boilers, combustion chambers and steam generators", "Nuclear energy and thermo-physics". Atomic energy booths and their information support are designed following curricula, programs, and educational standards. The new generation of interactive educational equipment (emulators) at the expense of a virtual laboratory workshop provides practice-oriented training of nuclear specialists. Simulators, training stands, visual aids, emulators, layouts of conventional equipment and interactive multimedia equipment for the "Thermodynamics and heat transfer", "Hydraulics", "Chemistry", "Power stations", "Electrical engineering and basics of electronics", etc. virtual laboratories were developed specifically to provide the educational process for the training of future specialists in nuclear energy [74].

The transition of nuclear energy to a higher technological paradigm prompted the creation of high-tech teaching aids in vocational education: simulators, emulators (NPP simulators), which are the most effective tools for forming professional competencies for the future NPP employees (figure 8). Such interactive teaching aids and visual aids allow for minimal material and resource costs to identify and consolidate students' causal links in the studied objects, phenomena, and processes [74].

We believe that it is essential to apply an integrated approach in the training and professional development of NPP personnel, namely VR and AR technologies, into distance learning platforms. For students and employees of different NPPs to have the opportunity to plan their study

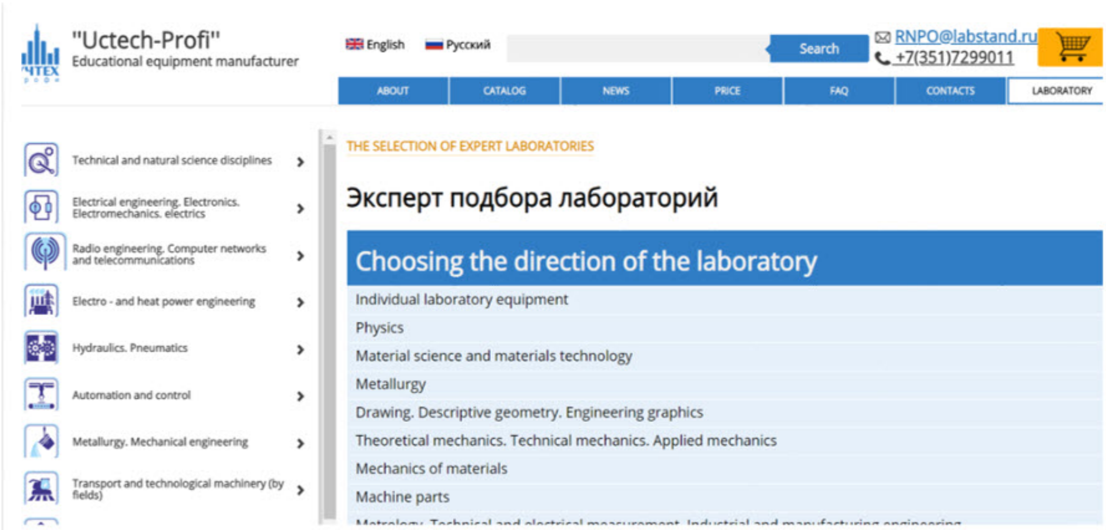

Figure 7: Materials on the site “Educational equipment”.

schedules, select the necessary sections, listen to lectures, and work with VR and AR technologies using various equipment.

2.5. Application of VR and AR technologies for the popularization of professions in the field of nuclear energy among children and youth

The nuclear energy sector is crucial for any developed country, as it is a supplier of electricity. Therefore, this industry needs new professionals and highly qualified specialists. There is a widespread stereotype that NPPs pose a significant threat to the population and the environment. Still, when you get acquainted in detail with the structure and principles of NPPs, it turns out that the routine operation of NPPs in comparison with other energy companies (CHP, TPP, HPP, etc.) have the least impact on the environment. This stereotype is why young people do not want to get an education in power engineering and nuclear power plants. Another reason is that today (in Ukraine) the current curricula “Physics 7-9th grades”, and “Physics and astronomy for 10-11th grades” provide for the study of topics: “Physical foundations of nuclear energy” (section “Physics of the atomic and atomic nucleus”, 9th grade); “Nuclear Energy” (section “Quantum Physics”, 11th grade); “Energy” (section “Technology” of the Integrated Course, 11th grade). These sections discuss the advantages and disadvantages of using nuclear energy, the development of Ukraine’s nuclear energy, ways to ensure the safety of nuclear reactors and nuclear power plants, the Chernobyl problem, the effects of atomic energy on the environment, protection from radiation, etc.

Researching the topic of Nuclear Energy, students should master the knowledge component, i.e., to know the principle of operation of a nuclear reactor, the effects of radioactive radiation on living organisms. They suppose to master the activity component to explain the ionizing impact of radioactive radiation, use a dosage meter, if available; as well as to use the acquired

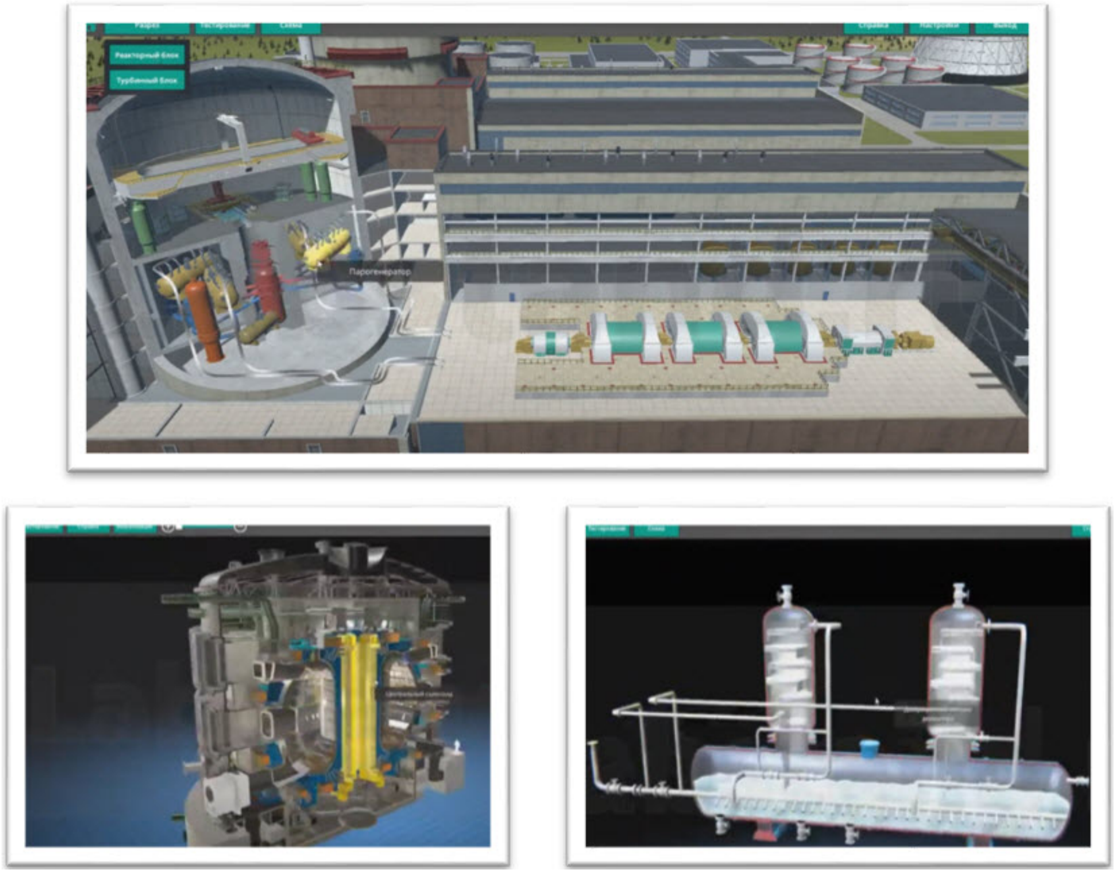

Figure 8: NPP virtual laboratory [74].

knowledge for life safety); the value component to realize the advantages, disadvantages, and prospects of nuclear energy, the possibility of using fusion, assess the feasibility of its use and nuclear on ecology, the efficiency of methods of protection against the influence of radioactive radiation. We believe that it is necessary to partially acquaint students with the topic of "Nuclear Energy" to expand children's general outlook about nuclear power plants' operation in grades 5-7 and carry out a wide range of career guidance activities. As NPPs are closed to a wide range of people, mostly schoolchildren, it is possible to use VR and AR technologies, which will help better understand the various physicochemical processes occurring at NPPs.

Play-based learning of students using VR and AR technologies motivates them to perform certain operations for a long time, receiving specific incentives (for example, to collect trophies or receive particular points). Learning through play, especially serious games that have in-depth content, quickly fascinate students. Games also promote the development of various skills and qualities, require players to solve multiple complex problems and require specific knowledge on a particular topic. Some – simply require general critical thinking. A variety of video games or simulators can currently teach students to study nuclear energy topics. Students can get acquainted with various aspects of NPP operation in an interactive form. We will describe some video games about the operation of nuclear power plants and other information resources:

1. **Nuclear Power Plant Simulator for Windows PCs** (http://www.ae4rv.com/store). In this game, you need to monitor the devices, troubleshoot, and monitor staff.

2. **Nuclear inc 2** (https://play.google.com) can be played on a smartphone (figure 9). Advanced functionality has been added to this NPP simulator, making it more challenging to operate a nuclear reactor. The player becomes a real engineer of famous atomic power plants, including the Chernobyl Nuclear Power Plant and Fukushima Daiichi Nuclear Power Plant. Unforeseen situations occur during the game – such as an earthquake, releases of radioactive substances, and fire. The player must monitor generators' temperatures, nuclear reactors, turbines, pressure levels, and the possibility of radiation. Besides, players are trained and told how different processes occur in the simulator and how people get electricity. Twelve levels of difficulty are available. In the first levels, the player monitors a small number of indicators. The next steps are complicated.

Figure 9: Nuclear inc 2.

3. **NPP before your eyes** (https://play.google.com) (figure 10). The game tells about radiation in nature and various areas of modern radiation technologies: medicine and agriculture. The game reveals interesting facts about nuclear energy and alternative energy sources. While playing it, you can learn about the specifics of building a nuclear power plant and test its strength with an intense hurricane. The application is adapted for students and audiences who do not have special education.

4. **Roblox Hyptek Nuclear Power Plant** (https://www.roblox.com). This game is a simulator of a nuclear reactor.

5. **Nuclear Power Station Creator** (https://store.steampowered.com) (figure 11). The game takes place in Japan to learn from your own experience of how nuclear power plants work. The player can operate the entire national network of NPPs and maintain its operation, monitor safety, and implement new technologies. As cities grow, their electricity needs increase, so nuclear power plants' requirements are continually improving. The player's task is to become a national leader in nuclear energy to prevent bankruptcy and decrease confidence in this industry.

6. **NPP simulator** on the site [74]. This resource contains various simulators designed to study the structure and principles of NPP operation.

Figure 10: "NPP before your eyes" game.

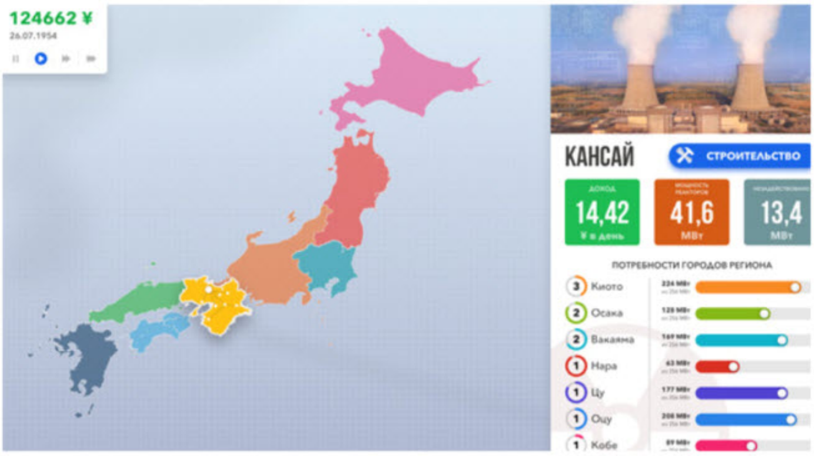

Figure 11: "Nuclear Power Station Creator" game.

7. Various **interactive quizzes and career guidance games** (figure 12) in the field of nuclear energy are posted on the website of the Information Center of the Atomic Industry [75].

Thus, the use of VR and AR technologies for play-based learning for children and youth in nuclear energy will increase interest in educational material through interactive content. It will speed up the formation of various skills and mastering knowledge, increase motivation for independent educational and cognitive activities by introducing the game, and competitive incentives. It will also intensify educational activities and help form a positive attitude to the nuclear energy industry, develop personal qualities (creativity, teamwork, etc.), increase the atomic energy professions' prestige, and more.

Figure 12: NPP Construction Game.

3. Conclusions

The VR and AR technologies rapid development has expanded the scope of their application and has led to the need for various studies and experiments on their application and effectiveness. In this publication, the authors carried out an analysis of the VR and AR technologies peculiarities for the training and retraining of NPP personnel was carried out and considered the following aspects:

1. *Application of VR and AR technologies for educational purposes.* Educational institutions apply VR and AR technologies for educational purposes. However, they do it mainly for the training of technical specialties. The research is being actively conducted on VR and AR training for specialists' exercise in multiple areas. In a few years, experimental data and results of such investigations will be available.
2. *VR and AR technologies application examples and trends in various industries.* Examples and directions of application of VR and AR technologies for different industries. Analyzing the international experience of using these technologies, we note that powerful companies and large companies have long used VR and AR in the sectors they operate.
3. *VR and AR technologies application examples and trends for NPPs.* The economic efficiency of using VR and AR for NPPs is achieved by eliminating design errors before the start of the construction phase, reducing time and costs for business trips of staff for staff professional development, increasing the level of industrial safety, and increasing management efficiency. Thus, VR and AR technologies for nuclear energy are successfully used in the following areas: modeling of various atomic energy processes, staff training,

and education; operation, repair, and maintenance of NPP equipment; presentation of activities, NPP construction.

4. *Peculiarities of application of VR and AR technologies for training of future specialists and advanced training of NPP personnel.* The highest requirements are set for NPP personnel training, as these stations are objects of critical infrastructure and must operate reliably and safely. The use of VR and AR technologies allows organizing staff training and carrying out advanced training in conditions close to real, safe for participants and equipment. VR and AR technologies are useful for working out the order of actions in the emergency mode; to optimize the temporary cost of urgent repairs; to work out dismantling/installation of equipment elements; to identify weaknesses in the work of individual pieces of equipment and the working complex as a whole. Besides, with the help of VR and AR, you can visualize the project for collective acquaintance, further adjustment, and joint decision-making in the framework of corporate activities. Therefore, it is essential to prepare training materials and develop using VR and AR technologies of various simulators and virtual laboratories for the nuclear power industry based on the best world practices.
5. *Application of VR and AR technologies for the popularization of professions in nuclear energy among children and youth.* Due to VR and AR technologies, the issues of "nuclear energy safety" have gained new importance both for NPP personnel and for the training of future specialists in the field of nuclear energy. It becomes possible to inform about the functioning of the atomic industry and prospects for the development of atomic power, as well as to increase the prestige of industry professions and popularization of science and digital technologies applying VR and AR to acquaint children and young people with nuclear energy in an interactive form.

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