Computer technologies in the system of training specialists for
the nuclear industry at ISPU

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Abstract. The article discusses the experience of effective application of computer technologies, trainers and simulators in the system of training specialists for the nuclear industry at ISPU. The necessity and relevance of using computer-based learning tools in the educational process is determined. The main stages of training specialists and the concept of multi-level training based on the wide use of computer technologies developed at ISPU are considered. The main advantages and features of using automated training systems, local computer simulators, functional analytical simulator, full-scale simulator, simulation tools, simulator of the basic principles of NPP operation, as well as packages of numerical and analytical methods of mathematical modeling in the educational process are shown. The directions for further improvement of the educational process at ISPU in order to increase the level of training of young personnel for the nuclear industry are shown.

1. Introduction

The reliability and safety of a nuclear power plant operation largely depends on the level of training and qualifications of specialists operating its equipment. They are required to have deep theoretical knowledge of the equipment and technological processes (nuclear-physical, thermal-hydraulic, physical-chemical), stable practical skills in operating the equipment and the NPP power unit as a whole. It is especially important to know and understand the regularities of the processes occurring in NPP equipment in non-routine and emergency modes [1].

The Ivanovo State Power Engineering University is currently working on the development of a new innovative educational program in the specialty "Nuclear Power Plants: Design, Operation and Engineering".

In the process of creating an educational program, the existing experience of the effective use of computer technologies, trainers and simulators in the educational process is largely taken into account.

2. Stages of training

The main focus of the professional activity of graduates of the specialty "Nuclear Plants: Design, Operation and Engineering", which ISPU prepares is the operation of nuclear power plants and their technological equipment. Therefore, the educational program focuses on the study of issues of operation and operating modes of equipment and power unit of nuclear power plants as a whole. Of great importance from the point of view of acquiring deep knowledge and the formation of professional competencies (which are largely based on the professional standards of the nuclear
industry) is a deep and clear understanding of the processes occurring in the main equipment (primarily in the reactor plant) in various operating modes, including emergency ones. It is also of great importance to acquire the primary skills for managing an NPP power unit [1, 2]. For these purposes, various types of computer simulators are the best suited, ranging from simple simulators to full-scale power unit simulators.

The following main phases can be distinguished in NPP operation [3]:
- observation and assessment;
- diagnostics;
- action planning;
- implementation.

To a large extent, the correctness of the operator's actions in the first three phases depends on the level of theoretical training and practical experience of actions in similar situations, i.e. on the level of development of intellectual skills. In the operator's actions during the implementation phase, motor skills are of decisive importance.

One of the ways to increase the level of training of specialists for the nuclear industry and the development of their intellectual skills is the widespread use of computer training tools in the educational process [4], which intensify the learning process, improve its quality and provide the required high level of mastering general scientific and professional competencies necessary for graduates for successful professional activity.

In accordance with the concept of multilevel training of specialists for nuclear power developed at ISPU based on the wide application of computer training technologies and computer training systems, the training process includes a number of stages. During each stage, certain types of necessary knowledge and professional skills are formed, it also ensures that students develop the required competencies. The computer training tools (training software) used at these stages are quite diverse. They can be broadly divided into two large classes. These are computer training tools designed to generate knowledge (the level of competence - "know" and partly "be able") and tools for the development of professional skills (levels of competence - "be able" and "own") [2].

The first include computer training systems with controlling units - CTS, virtual workshops, computer (virtual) laboratory work, and modeling and calculation programs. The second group includes conceptual, local and complex full-scale simulators - LS, FSS.

Structurally, the entire learning process can be divided into two phases: obtaining theoretical knowledge and practical skills. As the accumulated experience in the development and use of computer-based training systems in the training of specialists for nuclear power in ISPU shows, software training tools can be successfully applied both at the stages of theoretical and industrial training [5].

Continuous vocational training in accordance with the developed concept of multilevel training can be conditionally divided into the following stages [6]:
- Study of the theoretical principles of operation of the power unit (plant). Educational tool: automated training systems (ATS) in fundamental and general technical disciplines (technical thermodynamics, hydraulics and heat transfer, etc.). As a result of training, a set of fundamental theoretical knowledge is formed and fixed, which is necessary for understanding the principles of equipment operation.
- Study of specific equipment and technological systems, their design and schematic features. Educational tool: ATS on topics such as boiler and turbine plants, regeneration systems, condensation, deaeration and feed plants, etc. As a result of training, practical knowledge on structures, technical characteristics, technological schemes of equipment and systems of a power unit (plant), thermal and general efficiency of power plants is formed and fixed.
- Study of technological modes of operation and operation of power equipment, including the features of maintenance of certain types of equipment and systems. Educational tool: ATS on the basics of operating the main and auxiliary equipment, systems and the power unit as a whole. At this stage of training, practical knowledge is supplemented with certain intellectual
skills, such as concepts of the necessary conditions for start-up, shutdown and maintenance outage, about the types and causes of malfunctions during operation, ways to prevent and eliminate them, and the necessary control actions when maintaining the specified operating modes.

- Educational and training tasks on the simulators of a specific power unit or plant. Training tool: local or complex full-scale simulators, in which the composition and functions of individual systems or the power unit as a whole are modeled with varying degrees of completeness. At this stage of training, the intellectual skills for controlling the power unit are finally fixed and motor skills are developed.

3. The concept of multilevel training of specialists for nuclear power

The multilevel training system is shown in figure 1, it is implemented throughout the university learning, its individual elements are used in the disciplines of natural science, general professional and professional modules. This system influences the formation of the necessary competencies of nuclear power specialists. The traditional learning scheme operating in all universities organically includes: extended physical and mathematical training of future specialists, educational and methodological automated complex, computer virtual simulation of nuclear power plants, pre-training and training simulator, as well as industrial and pre-diploma practice at workplaces.

![Figure 1. Training system.](image)

For training at the first three stages of continuous professional training, automated training systems (ATS) are used, which include a set of automated training courses (ATC) and, if necessary, local computer simulators (LCT) [3].

Automated training courses allow students to understand the theoretical foundations of the operation of equipment and systems of an energy facility, to study the design of equipment, operational schemes, protection, blocking, etc., as well as the operation of equipment and systems. ATC equipped with a block of control questions can be used in the mode of programmed training, self-training and knowledge control [7].

Local computer simulators, with varying degrees of detail simulating technological processes in individual systems and types of equipment, allow the formation of professional skills and the ability to make and implement decisions on the management and maintenance of objects considered in the content part of the ATC.
Thus, pre-training allows studying the necessary theoretical courses, technological equipment and operating modes of the NPP unit as a whole, unit switch-gallery, alarm and controlling elements necessary for controlling the NPP unit.

At the stage of pre-training, an educational and methodical automated complex (EMAC) is used, designed for obtaining special theoretical knowledge and their automated control (testing) using a personal computer (PC). EMAC also allows preparing students to work on a functional and analytical simulator (FAS). EMAC includes computer training systems (CTS) developed jointly with Rosenergoatom concern JSC [8].

Virtual simulation of nuclear power plants connects the knowledge gained from previously completed courses into a single system that allows understanding the functioning of nuclear power plants as a single "organism". The virtual simulation system used on the 3KeyMaster platform is a unique software technology that allows covering many aspects of modeling thermal and nuclear power plants, including automated control systems [9].

Preliminary training of students takes place on a computer simulator - FAS (a computer copy of a full-scale simulator), which allows each student to independently control the NPP unit from their computer.

Simulator training using FAS (figure 2) allows [8]:

• understand the principles of controlling individual units of the unit using separate control panels of the NPP unit switch-gallery;
• acquire skills in controlling the nuclear power plant unit in the main and emergency modes of operation;
• combine all previously acquired knowledge and training to manage the unit at the NPP unit switch-gallery;
• freely master the latest technologies;
• prepare operational personnel to act in emergency situations.

The functional analytical simulator is a complete electronic copy of the FSS, which allows the student, in the course of individual work, to master the appearance and mutual arrangement of the control and monitoring bodies, as well as the principles of working with them [10]. FAS is considered both as an independent element of training in a number of disciplines, and as a preparatory stage for work at the FSS.

Figure 2. Appearance of the functional and analytical simulator.

The final stage is simulator training on a full-scale simulator (FSS), the appearance and arrangement of the panels of which corresponds to the unit switch-gallery of a power unit with a VVER-1000 reactor and provides real-time simulation of NPP operation modes. Special functions of the simulator control allow the teacher (instructor) to form the necessary initial states and scenarios of
training sessions, to demonstrate the studied modes, to control the progress of the process during independent work of students, to analyze their actions. Control functions for equipment outside the unit switch-gallery and control over its condition are carried out from the instructor's workplace. The FSS has a set of initial states necessary for modeling all modes of operation and providing a quick transfer of the simulator to the state required for a training session. In addition, the FSS allows the user, in the process of modeling the modes, to independently create and memorize the initial states required for training sessions [8].

The use of FSS in the educational process (figure 3) plays a significant role in ensuring the required quality of graduate training. The FSS is a software and hardware complex using a full-scale model of a real power plant and a complex all-mode mathematical model of a power unit. It allows the student to perform the same actions as the operator on the prototype power unit's unit switch-gallery, and allows combining all previously acquired knowledge.

![Figure 3. Training students on a full-scale simulator.](image)

ISPU has developed unique techniques for modeling on a computer and full-scale simulator of an NPP power unit a number of different technological modes that are of interest as educational tasks [11]:

- simulation of normal (non-emergency) shutdown of the power unit with the transfer of the reactor unit to the "hot" state and start-up from the achieved state with the output of the reactor unit to the power level;
- simulation of protection and blocking actions;
- simulation of neutron-physical reactor measurements.

These modes involve interaction of the simulated power unit equipment and a person (the power unit operator) in a wide range of changes in technological and operational parameters, and the methodological support is focused on the analysis by students of the processes occurring in the equipment, including in modes with violation of normal operation and emergency modes [12].

The scope of simulation on the simulator includes standard failures for typical equipment, such as regulators and control valves, pumps, fans, sensors, valves, remote-controlled switches, check and safety valves, etc. It is possible to simulate a wide range of modes with a violation of normal operation, including those associated with equipment failures and the protections themselves [13].

Acquaintance and mastering by students of the technique of a physical experiment and its processing (using specially created computer programs for this purpose) is also one of the most important tasks in the training of specialists who will design and operate nuclear power plants.

It should be noted, that when creating computer simulator systems, it is justified to use simulation mathematical models. In particular, the development of simulation mathematical models of the core of a nuclear reactor continues to be an actual direction, despite the presence in Russian and world practice of a sufficient number of high-level developments, including specialized calculation codes.
This is explained by the fact that high-level software developments are usually intended either for use in full-scale simulators, or for accurate studies of normal, transient and emergency processes in the core, i.e. they are “pedagogically neutral” and available to a limited number of people with special physical and mathematical training (a vivid example of a technical approach to design, which, however, is justified by the purpose of models).

At the same time, the level of safety during the operation of a nuclear power plant, to the extent that it is determined by the human factor, depends on the mass level of safety culture of operating operational personnel. Setting the ultimate goal of computer training technologies to develop intellectual skills for safe reactor control, it is natural to rely on a systems-engineering approach when developing simulation models.

Thus, the developed universal software package “Simulation spatially distributed model of the VVER reactor core” allows to implement a systems-engineering approach in modeling by adding or replacing elements that make up the software package, as well as by increasing it to a volume corresponding to the set educational task [14].

The core of the software package is a module that initializes the actions of all other programs connected to it according to the semaphore principle with an interval corresponding to the setting of the software timer.

The software package was verified on the example of specific reactor plants V - 320, V - 446, V - 407. The discrepancy between the parameters and the design values in steady state conditions was no more than 3%.

The possibility of further development of a software package based on FTN technology is seen in two directions [14]:

1. the use of more advanced models of nuclear-physical processes in the core in order to formulate the appropriate educational and training tasks;
2. expanding the topographic range of modeling (closing the core model to the model of the main circulation loop, as well as connecting the models of secondary loop systems, etc.).

The issue of integrating this development with the mathematical model of the reactor is reduced, obviously, only to the problem of their standardization at the level of an external database.

It should be noted that the simulators of the NPP power unit are used in the disciplines of the professional module, being the final step in the multilevel system of software and hardware, such as automated training systems that simulate complexes of thermal-hydraulic, neutron-physical and technological processes, local-situational simulators of individual systems, etc.

One of the elements of competence that affects the speed and efficiency of its formation is such a factor as the individual personality traits of the student. The study of this problem is realized due to the full-scale simulator available at ISPU, which is unique within the university. Students with different levels of success in fulfilling the tasks of simulator training revealed significant differences in the indicators of the severity of personal qualities. Their analysis makes it possible to develop the methodological aspect of training on the basis of both complex solutions and individual recommendations to students within the framework of a competence-based approach [13].

4. Simulators of basic principles of operation

In the system of continuous professional training, relatively simple and low-cost training programs - the so-called concept simulators, or simulators of the basic principles of operation (SBP) - are of great benefit. They allow to acquire the necessary knowledge and develop intellectual skills for controlling the power unit (i.e., they can cover such phases of the operator's activities as assessment, diagnostics and action planning). A package of such programs allows to “play” the most crucial moments of future professional activity and independently assess the level of knowledge and skills while preparing for the exam at the next stage. Indeed, working on such a simulator, the student should eventually get a clear idea of the need for certain actions, as well as the impact of one or another operating parameter on efficiency and safety, which will allow him to consciously perform the actions prescribed by the operating instructions [6].
In the personnel training system, SBP takes an intermediate place between theoretical training and training at FSS and FAS. SBP can be a part of ATS at any stage of training as a tool for controlling intellectual skills or supplement ATS as an independent educational tool [15].

Unlike FSS, the SBP does not require accurate reproduction of information and motor fields of a real power unit. Of the entire array of operational information, the student is offered only that which is necessary for solving a specific problem. Accordingly, priority is given to fixing not motor, but intellectual skills according to the basic principles of management in a particular situation on a limited (foreseeable) list of technological systems.

The term “fixed intellectual skill” can be defined as whether the personnel have a clear idea of the current state of the technological process, the need (or no need) to perform a particular action and the impact of this action on efficiency, reliability and safety.

General characteristics of SBP as an educational software product [6]:
1. Game interface that creates interest in working with the program, a small number of controls and output parameters, the presence of windows for displaying messages, graphs, tips, ratings and comments, etc.
2. The presence of a block of questions in the form of local operational tasks with complete scenarios, including an assessment of the actions performed.
3. Local mathematical model with a limited composition of equipment and the boundaries of consideration of technological modes.

With the use of SBP, tasks of maintaining the operating modes of individual technological systems and the power unit can be implemented as a whole (start-up, shutdown, load change, etc.), as well as studying the effect of various operating and design parameters on thermal efficiency [9].

Working with SBP consists of answering a series of questions grouped by topic. Each question is illustrated with a fragment of a schematic diagram of a technological system or a power unit as a whole. This displays the initial values of some parameters of the mode and the necessary controls. The answer is required to indicate in which direction (or to what limit) these parameters will change when the proposed control action is implemented. After receiving the answer (and in some cases in the process of thinking it over), the program allows to make a trial impact, after which its results are shown on the graphs. The answer to the question is accompanied by discussion, commentary and assessment [7].

The advantage of the basic principles simulator is the relative simplicity of the used mathematical models and their adaptation to various types of equipment.

5. Packages of numerical and analytical mathematical modeling
For the purpose of teaching at all stages of the multi-level concept of education, ISPU uses numerical and analytical methods of mathematical modeling of the operation of nuclear power plants and their main units. At that, accurate analytical models are used to verify and determine the tuning factors to improve the accuracy of numerical models. The calculation results obtained with the help of modern numerical and mathematical modeling packages can help to fully study each object of research and the processes occurring in it, to carry out work on it to optimize the its operating modes and its design, to modernize it, and to predict the effectiveness of these measures.

ISPU uses many years of experience in application the most famous numerical and mathematical modeling packages (Mathcad, MATLAB, MS Excel, ANSYS Fluent, COMSOL Multiphysics, FEMLAB, FlowVision CFD, etc.) with the aim of learning and training specialists for further design, research, production-technological activities. The application of numerical modeling in practice is preceded by deep theoretical training and the study of the foundations and methods of mathematical modeling [15]. There is a formation of skills in using mathematics as a necessary tool in modern professional activity, the acquisition of practical skills in the application of mathematical methods to solving applied problems, the acquisition of skills in the development, research and use of appropriate mathematical models of physical and technical processes, phenomena and systems, as well as the
formation of skills in using a complex of applied programs. This allows to significantly improve the quality of education, leads to a deeper mastering of professional competencies.

In the educational process, when mastering numerical and mathematical modeling packages, students are assigned various engineering tasks - solving equations and studying functions by numerical methods, modeling and analyzing various mechanisms of heat transfer, neutron-physical processes, tasks of creating models and studying the operation of nuclear power facilities [16]. An example of the solved task of engineering analysis is shown in figure 4. The goal of the task is to create a numerical model of the PGV-1000M steam generator (SG) by students in the ANSYS Fluent software system, as well as the subsequent study of the created model and its verification.

Figure 4. The result of solving an engineering task of modeling the operation of SG:
  a) the distribution of absolute pressure in the steam volume of the SG and
  b) visualization of trajectories of moisture droplets with a diameter of 50 microns.

Solving similar engineering tasks in nuclear education plays a key role in the formation of a specialist's professional competences, his ability to design new equipment and recreate models of the existing one for optimization and modernization aims. A nuclear specialist, using numerical modeling in the course of solving engineering tasks, acquires skills in analyzing available and received information, predicting the state of equipment and the course of processes.

At ISPU numerical modeling is used throughout the educational process: when studying the disciplines of natural science, general professional and professional modules, when conducting research work, as well as when preparing a final qualifying work. The acquired knowledge and skills are applied by graduates in the workplace.

6. Conclusions
Ivanovo State Power Engineering University named after V.I. Lenin (ISPU) has been producing specialists for the nuclear industry for more than 20 years. During this time, colossal experience has been accumulated, and a methodological and material-technical base has been formed, focused on training the operating personnel of NPP units. In particular, within the framework of this database, there are and are actively used:

- full-scale simulator (FSS) of the unit switch-gallery of a power unit with a VVER-1000 reactor,
- functional and analytical simulator, which is a complete electronic copy of FSS,
- pre-training and virtual simulation classes.

These training tools are organically integrated into a single system. Application of this system allows the training of future specialists to be carried out in full compliance with the requirements of the Federal State Educational Standard and recommendations of employers. At the same time, the result of education is the graduate's competences, characterizing his ability to apply knowledge, skills
and abilities for successful professional activity. As practice shows, the terms of adaptation of young specialists in production due to the application of this approach are significantly reduced.

The direction for further improvement of the educational process at ISEU can be the attraction of highly qualified specialists from the basic enterprises of the nuclear industry for the purpose of internal motivation of students in the course of familiarization with the work experience of these specialists. Due to such cooperation, the distance between the university and employers can be reduced to a minimum.

The introduction of a new innovative educational program that combines advanced technologies and the indicated long-term experience in using computer technologies, simulators of various levels will help to raise the level of young personnel training for the nuclear industry to an even higher level.

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