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Computer modeling and simulators as part of university training for NPP operating personnel

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Abstract. This paper considers aspects of a program for training future nuclear power plant personnel developed by the NPP Department of Ivanovo State Power Engineering University. Computer modeling is used for numerical experiments on the kinetics of nuclear reactors in Mathcad. Simulation modeling is carried out on the computer and full-scale simulator of water-cooled power reactor for the simulation of neutron-physical reactor measurements and the start-up - shutdown process.

1. Introduction
Russian nuclear power industry is developing actively, on a very large scale: by 2030 it is intended to more than double electric power generation from nuclear power plants [1]. Among the preconditions for fulfilling these plans anticipative training of personnel engaged in operating nuclear power plants’ power units. Furthermore, highly trained personnel servicing nuclear facilities are a major factor guaranteeing their reliable and safe operation. It has been variously estimated that 15–40% of all accidents and 20–80% of all case of malfunction at nuclear power plants are attributable to the operators concerned [2]. The effective work of higher educational institutions should be directed towards solving the above problems. Computer technologies are commonly known to be highly effective in university training of future nuclear power plant personnel [3 – 6]. We offer a unified set of training programs intended to intensify university training of future senior reactor control engineers. The subject of our study comprised water-cooled power reactors as the most widespread worldwide.

2. Set of training programs
The set of training programs is based on a competency approach, which presupposes that the results of education should be evaluated not by the sum total of acquired knowledge, but according to the graduate’s competence, defining his or her ability to apply knowledge and skills in successful professional activity as a result of profound understanding of the physics of the process under examination. This is achieved by integrating the use of computer and imitative simulation within a single conceptual framework.

The set of training programs consists of three parts. The first includes a laboratory-based computer practical for water-cooled reactor kinetics that we developed on the basis of numeric experiments [7, 8]. The second part of the training programs set is devoted to simulation of neutron reactor measurements [9]. The third part provides procedural guidelines for simulation of generating unit startup and shutdown on computer and full-scale simulators for nuclear power plants using water-cooled reactors [10].
2.1. Numerical experiments on the kinetics of nuclear reactors

An in-depth study into neutron processes is based on numerical experiments conducted as part of an in-house computer software package. Mathematical models encompass the cold and hot reactor kinetics. They make it possible to analyze the role of delayed neutrons, the fuel and coolant temperature effects on the nature of transients, fuel burnup, the reactor xenon and samarium poisoning, as well as xenon oscillations and the reactor xenon stability. Mathematical models are based on a system of stiff nonlinear differential equations integrated using the respective Mathcad algorithms. The use of this environment makes the process of modeling highly graphic and convenient for numerical experimentation while allowing students to manipulate with different input parameters, assess their role and undertake a research of their own. When transients are modeled, attention is given to the problem of closing the system of differential equations, which is not just a mathematical problem but is also of a practical importance allowing conditions to be formulated for analyzing the operation of interacting components of the unit’s process circuit. Besides, students learn to be able to consider interlinked transients in components not only based on numerical experiments but also using a qualitative analysis of differential equations without solving them.

For illustration, we shall consider a mathematical model for excitation and suppression of axial xenon oscillations in a nuclear reactor allowing students to explore this challenging and operationally important problem. Numerical experiments to model xenon oscillations are based on a system of two similar coupled reactors with an equal energy release and contacting ends. This system of reactors is a model of one reactor divided vertically into two identical halves. The exchange of neutron fluxes between these reactors is through the neutron leakage via the contacting ends. Xenon oscillations between the reactor’s upper and lower halves are excited through the excitation of one reactor half by an oscillation introduced into it in the form of a reactivity leap, while the suppression of the introduced oscillation is modeled by boron regulation acting on both reactor halves. The consideration is based on a “pointwise” model of the reactor in a two-temperature approximation for fuel and coolant with the xenon birth and death equations added to it. Since the transient is slow, no delayed neutrons affect it in any way, and these may be neglected whatsoever, that is, all neutrons may be treated as instantaneous or a single-group approximation may be used. In the investigated model, the axial xenon oscillations were suppressed through a temperature reactivity effect and by reducing the time of the neutron flux exchange between the coupled reactors. Based on the presented numerical experiments, curves are plotted by students to define the boundary between the xenon stability and the reactor instability. Oscillations are growing in the xenon instability region and fading in the stability region. The transition from one region to the other is characterized by sustained oscillations.

2.2. Simulation of reactor measurements

The second component deals with the reactor neutron measurements based on a full-scale simulator and a computerized functional analytical simulator.

The simulator complexes are based on mathematical simulation of neutronic, thermal-mechanical, thermal and other processes and the resulting creation of a generating unit functioning model for various real-time operating modes. The analytical simulator is developed on a PC using 3KeyMaster™ software from Western Services LLC [11]. The extensive capabilities of the analytical simulator permit experiments above the reactive core and simulation of normal and emergency situations, while the mobility and convenience of using personal computers facilitates effective use of analytical simulator during training. 3KeyMaster™ is a modeling platform, multi-purpose environment for developing, debugging, execution, testing, integration and final operation of models. Tools of this environment are a set of object-oriented graphical modeling tools with built-in algorithms for numerical solution. 3KeyMaster™ is widely used in a variety of simulators worked worldwide during the training of operators. Simulator interface includes operators and instructors’ rooms. The main working window in both modes can be used for:
– the output of layout for panels and consoles with the ability to transition to their graphic imitations, repeating the relative position of the control and management, technological lines, alarm display, panels and consoles of real block control panel;
– the output of concept displaying the main technological parameters and operational condition of the equipment with the ability to transition to the unwrapped schemes of most systems.

Management of simulated processes can be made both by panels and consoles impacting on the image of control keys, mode switches, setting devices and controls; and by the schemes of technological systems by changing the options. Full-scale simulator can be used for simulating of reactor measurements. Full-scale simulator has identical software in addition to a full-scale model of a real control room.

It should be noted that reactor measurements are not quite adequately covered by the existing university programs and respective guides. However, a nuclear reactor can be safely started up and further operated only when its neutron performance is known as exactly as required by nuclear safety and core thermal reliability regulations. Familiarization with and mastering of the physical experimentation technology during education is one of the most important tasks in training of personnel who will be in charge of nuclear reactor control.

Each laboratory task concerning reactor measurements includes a theoretical section; an experimental section that includes existing methods of neutron measuring on existing equipment adapted to computer imitators; a practical section comprising programs for and methods of processing experimental data. In the course of fulfilling each task, students perform appropriate actions on simulated control units, controlling current processes both with the help of control units and the available possibility of graphically recording the dependence of various parameters on time. Results are processed on the basis of saved graphic or digital experimental data. Computing required neutron characteristics by means of the simulated reactive core, creating graphic data, determining measurement errors are carried out.

The practical includes the following experiments:
– simulating reactivity meter work;
– determining temperature, barometric and density coefficients of reactivity at various reactor power levels;
– determining differential and integral efficiencies of reactor control and safety system control units and reactivity coefficient regarding reactor boric acid concentrations at minimal controlled power level;
– determining efficiency of reactor emergency safety and of the most efficient reactor control and safety system unit;
– determining the power coefficient and power effect of reactivity with reactor power increased from minimal controlled level to 1% of nominal value.

2.3. Simulation of unit startup and shutdown
The closing component is simulation of the NPP unit processes, specifically the unit startup and shutdown. The guidance for this component has been developed based on the plant’s model stepwise startup/shutdown program with regard for the standard list of startup/shutdown operations, as well as the procedures for and the sequence of these. This training component makes it possible for students not only to study the action of the unit components but also to explore the interlinking among them, solidify and systematize theoretical knowledge, and acquire primary skills in operating complex facilities.

Simulator training promotes the formation of occupational mentality and is an effective tool for the personal development of future staff and is an aid for the improvement of occupationally important traits. Therefore, simulation of startup/shutdown operations includes investigations to identify the individual and personal qualities that define the degree of success achieved in performing simulator tasks. Personal qualities are a component of competences that has an effect on the rate and efficiency of their formation. Students with different simulator work efficiencies exhibit a greatly differing extent
to which their personal qualities are pronounced. Analyzing these qualities makes it possible to evolve the guidance aspect of training based both on integrated solutions and on individual recommendations to trainees.

3. Conclusion

The computer technologies developed and described above have been introduced into the whole range of subjects and are used as the basis for students’ research training and graduation papers. The share of job-related subjects which involve mathematical modeling and simulation amounts to more than 35%. As reported by the leaders of respective plant departments, this leads to the time for the university graduates to adapt themselves to the real plant environment cut by a third or even by half.

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