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TRAINING AND PERFORMANCE ASSESSMENT OF NPP OPERATORS ON COMPREHENSIVE SIMULATORS

Abstract. A methodology for assessing and monitoring the activities of nuclear power plant operators during their training at training complexes is proposed, based on the concepts of “initiative” and “prohibited” combinations introduced in the article in the transformation matrices that characterize the current activities of nuclear power plant operators. For its practical implementation, a three-level structure of the criterion for monitoring and evaluating the actions of an operator (a group of operators) is proposed.

*Keywords***:** nuclear power plant operator (a group of operators), training complex, “initiative” and “prohibited” combinations, multi-level criterion for control and evaluation

Introduction

Currently, the problem of improving operator activity has become particularly acute in modern control systems for technological processes and complex objects. The safety of nuclear power plants (NPP) directly depends on the reliability of equipment and personnel. One of the determining parameters of personnel reliability is the error-free actions of a person, especially a human operator. According to various estimates, from 15 to 40% of all accidents and from 20 to 80% of all violations at nuclear power plants, including the most serious ones, are directly or indirectly associated with errors by personnel at nuclear power plants [1-3]. Analysis of the causes and consequences of the accident at the Three Mile Island (USA) nuclear power plant in March 28, 1979 led to a comprehensive review of approaches to nuclear power plant safety and recognition that humans are an important link in ensuring the safe operation of nuclear power plants. Not only the effectiveness of performing the tasks assigned to them, but, in some cases, the integrity of the situation and the safety of people depends on the correctness of his actions, the ability to find the correctness and implement the correct solution to the problem [4-6,10].

At the same time, the term “human factor” was introduced, laboratories were also created to study the possible errors of a human operator, and methods appeared for studying possible errors when performing various technological operations of nuclear power plant operation, including during repairs. The job of nuclear power plant operators is extremely difficult. Operators must not only know the purpose of each device and the meaning of each signal, but also understand what actions to take to ensure normal operating conditions, as well as in the event of equipment malfunctions and accidents. Despite the fact that they always have appropriate detailed job descriptions at their disposal for all operating modes of the power unit, but the amount of information is very large and the responsibility for the actions performed is very high. In this regard. The research of American colleagues on addiction is of interest the probability of human operator error depending on the level of his training. Probability of error when completing work within the allotted time less when knowledge in the learning process is transformed into skills. These dependencies are the theoretical basis of education and training. For example, a model of human behavior has been developed that takes into account that the probability of an error depends on the natural abilities of the human operator and his training (Human Cognitive Reliability - human reliability as function of his abilities) [7]. A detailed analysis of the causes of the Chernobyl disaster revealed the underlying causes of the accident, which ultimately led to the emergence of the term “safety culture” generally accepted in the literature [8].

Erroneous actions of personnel can be divided into three categories:

- random error-miss;
- mistake due to ignorance;
- deliberately wrong action.

Most often, the errors of nuclear power plant operators contain elements of different categories. There are many other classifications of personnel errors, but it is much more important to know the causes of errors. Almost all researchers the role of the human factor in nuclear energy and the root causes mistakes made by NPP personnel are the following: improper organization work and management (including supervision, control, coordination of interaction between departments); erroneous communication; poor staff training; personal qualities (inattention, arrogance, non-compliance with procedures, etc.) [5,6,11].

It is known that the most effective technical means of training operators of various types of professional activities are simulators [9]. Recently, simulators are increasingly used in industry, energy and other sectors of the national economy, in particular, for training operators of nuclear power plants, characterized by the complexity of control tasks. The methodology proposed in this article for assessing a nuclear power plant operator when training him on a simulator is focused on the “instructor-operator” scheme, which in this case can be represented by the structure shown in Fig. 1. Here the instructor acts as the teacher, and the operator (group of operators) acts as the student.

The main elements of the above structure are the instructor, the human-operator (group of operators), the subsystems “Operator”, “Control and Evaluation”, and “Expert”. The functions of the instructor include assignment and control of the overall learning process. If necessary, the instructor can create one or another emergency situation during the training process. The “Expert” subsystem, based on the initial test task, generates the corresponding reference implementations, on the basis of which a comparison is made with the real work of the operator (group of operators) and an assessment of his (their) activity is formed. The "Control and Evaluation" subsystem implements the operation of a multi-level hierarchical system of evaluation criteria and ensures documentation of the learning process.

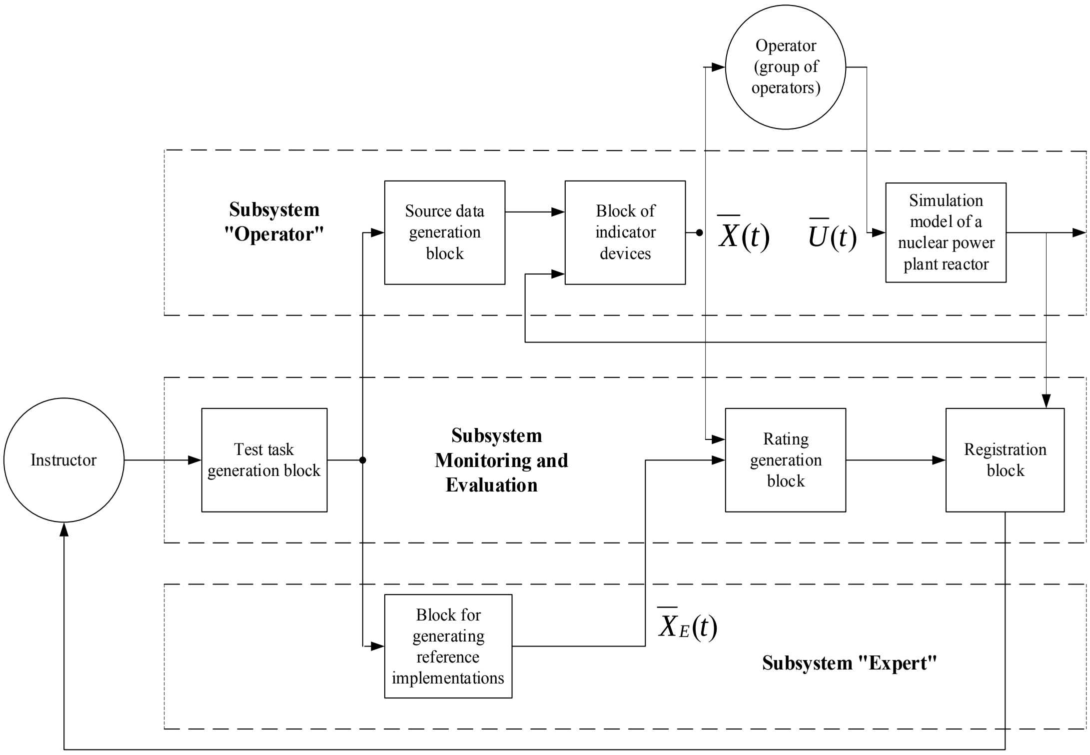

Figure.1. Block diagram of the “instructor-operator” of the complex simulator

Below we propose an effective methodology for assessing and monitoring the activities of NPP operators during their training on simulator complexes, based on the concepts of “initiative” and “prohibited” combinations introduced in the article in the transformation matrices that characterize the current activities of NPP operators.

Mathematical model of discrete states of NPP control panels

To ensure the possibility of monitoring and assessing activities when training NPP operators on simulator complexes, it is proposed to represent their work with some current model, reflecting a consistent change in the current state of discrete controls on the NPP control panel in comparison with the reference model of its activity (Fig.2).

When assessing the activity of a nuclear power plant operator, two levels (0.1) were adopted to record the state of each control element. These levels correspond to the physical states of controls such as “on-off”, “minimum - maximum”, “press and release”, etc.

To monitor and evaluate the activities of NPP operators during their training at simulator complexes, it is proposed to use a three-level structure of control and evaluation criteria - “task-mode-parameter” [10]. According to the adopted structure, the lower level of the hierarchy is the criteria for assessing the operator’s activities according to parameters, which in this case are taken to be the state of the controls in a separate mode.

Figure 2. Control panel of the 3-rd and 4-th power units of the Chernobyl NPP

Since the main unit in such a structure is a separate mode, it is obvious that the creation of a reference model involves first of all the creation of a reference transformation operator $Q_{refj} = \{a_{ik}\}^{j}, i = 1,2,\dots,N^{j}_{0ref}, k = 1,2,\dots,N^{j}_{0}$, each j-th mode and the initiative (current) transformation operator $Q_{initj} = \{a_{ik}\}^{j}, i = 1,2,\dots,N^{j}, k = 1,2,\dots,N^{j}_{0}$. In this case, is a matrix reflecting the sequential change in the current state of the discrete controls of a given mode. Moreover, if the number of columns of such a matrix N^{j}, determined by the number of controls, for each mode is a completely definite and unchanged value, then the number of rows N^{j}_{0}, determined by the number of discrete operations performed by the NPP operator, is ambiguous due to the functional characteristics of a particular NPP operator.

Therefore, the Q_{initj} matrix is variable depending on the specific operator and the degree of its preparedness, in which only the first and last rows do not change. The first row of the matrix Q_{initj} is the initial state of the controls at the beginning of the j-th mode. The last line is the specified final state of the controls, determined by the training task for practicing the j-th mode. In the reference transformation matrix Q_{refj}, the number of rows is regulated by a given sequence of switching controls of the j-th mode. The reference matrix Q_{refj} will only be unique if, when working out the j-th mode, arbitrary and simultaneous switching of controls is not allowed. Most modes are characterized by situations where the operator can simultaneously and arbitrarily, within the permissible switching of controls, perform the assigned task. Taking into account the above, it is proposed to use the first and last rows of the matrix Q_{refj} as a standard, with current monitoring of the possible occurrence of “prohibited” combinations of the control state vector, determined by the matrix $Q_{prj} = \{c_{ik}\}^{j}, i = 1,2,\dots,N_{prj}^{j}., k = 1,2,\dots,N_0^j$. Wherein the number of "prohibited" combinations N_{prj}^{j} is determined by experts for each j-th mode of the educational task. By "prohibited" combination we mean those sets of states of control bodies, obtained on the basis of an analysis of the work of NPP operators, that in real conditions lead either to a failure of the j-th mode or to an emergency state of the NPP.

The work of a nuclear power plant operator must be accompanied by the mandatory issuance of information (messages). The absence of a message is considered an error, which can be corrected in the course of further work. If one of the rows of the initiative matrix coincides with one of the rows of the Q_{prj} matrix, the task of working out the j-th mode is considered unfulfilled and is assessed as unsatisfactory.

When the mode is fully executed (in the absence of coincidences between the "initiative" combinations and the "forbidden" ones), the "initiative" matrix is worked out according to the methodology outlined below.

Multi-level criterion for monitoring and evaluating discrete operator actions

An analysis of the professional activity of a nuclear power plant operator shows that his activity is quite accurately characterized by the speed, accuracy (reliability) and intensity of his work. To assess the operator's activity in the sense of its reliability (error-freeness), as indicated above, two levels (0 or 1) of recording the state of each control were adopted. In this case, as stated above, the state of each k-th control at the moments of execution of the j-th discrete operations is determined by the column of the initiative matrix

$$Q_{initj} = \{a_{ik}\}^{j}, i = 1,2,\dots,N^{j}, k = 1,2,\dots,N_0^j, \tag{1}$$

which reflects the sequential change in the current state of the controls in the j-th mode.

If we accept that during the execution of the j-th mode, each control must be at some point in time transferred from one extreme state (0 or 1) to another (1 or 0, respectively) and maintained until the end of the mode, then the appearance of any other intermediate switching's indicates the presence of errors in the operator's actions. In this case, the number of errors n_{esti}^{j} for the k-th control can be determined as

$$n_{esti}^{j} = \frac{1}{2}\left[\sum_{i=2}^{NJ}\left(a_{ik}^{j} - a_{i-k,k}^{j}\right) - 1\right]. \tag{2}$$

Then a quantitative assessment of the reliability (error-free) of the operator's work, when executing the j-th mode, a criterion of the form can be used

$$I_{estj} = \sum_{k=1}^{N_0^j} a_k^j / 2\beta_k^j\left[\sum_{i=2}^{NJ}\left(a_{ik}^{j} - a_{i-k,k}^{j}\right), \tag{3}$$

where a_k^j – coefficient of importance of the k-th control body, and $\sum_{i=1}^{NJ} a_i^j$=1; β_i^j – binding and normalization coefficient in the range [0,1].

It should be noted that in the j-th mode there are cases when the k-th control element can change along the chain 0(1)→1(0)→0(1) →…. Then formula (3) will take the form

$$I_{estj} = \sum_{k=1}^{N_0^j} a_k^j / 2\beta_k^j [\sum_{i=2}^{N^j} (a_{ik}^j - a_{i-k,k}^j) - b_k^j], \quad (4)$$

where $b_k^j = 1$, if the k-th organ changes along the chain 0(1) →1(0); $b_k^j = 2$, if 0(1) →1(0) →0(1); $b_k^j = 3$, if 0(1) →1(0) →0(1)→1(0), etc.

Depending on the number of errors and the selected scale, the assessment takes on specific numerical values in the normalized range [0,1].

The intensity of activity of a nuclear power plant operator is characterized by the general reaction of the body to the influence of the information flow and is assessed using a number of physiological indicators (electroencephalogram, cardiogram, etc.). In particular, one of such criteria for assessing the operator's overall tension in the j-th mode is a criterion of the form:

$$I_{tenj} = \sqrt{\frac{1}{n} \sum_j^n (\frac{y_j}{y_{jmax}})^2} \quad (5)$$

where y_{jmax} – maximum values of selected physiological indicators; y_j – values of the same indicators under given operating conditions.

The lack of possibility of digital imitation of an operator from the point of view of his physiological state in the process of performing a training task leads to the fact that his activity is subsequently assessed only by two parameters: reliability and speed. This, however, does not exclude the assessment of operator tension during the practical implementation of the training complex.

To estimate the performance of NPP operators during the execution of the j-th discrete operation, we take the time

$$\tau_{esti} = \tau_{hidi} + \tau_{moti}, \quad (6)$$

here τ_{hidi} – hidden reaction time of the NPP operator (usually ≈ 2 s), defined as the time interval from the moment the signal for processing appears until the operator's response to it; τ_{moti} – the motor reaction time, which is defined as

$$\tau_{mot} = b \times log_2 \mu_i, \quad (7)$$

where b=0,074; $\mu_i = 2R_i/Q_i$ – complex coefficient of difficulty of the work performed; R_i – the distance of movement of the control, Q_i – the width of the control itself.

Taking into account the time of receiving and perceiving information τ_{infi}, as well as the time of analysis and decision-making τ_{deci}, the total time for performing the j-th discrete operation is determined as τ_{geni}

$$\tau_{geni} = \tau_{esti} + \tau_{infi} + \tau_{deci}. \quad (8)$$

Then, the total execution time of the j-th mode is determined by the sum of the execution time of the i-th operations in this mode, that is

$$\tau_i^j = \sum_{I=1}^{N^j} {}_{geni}, \quad (9)$$

where N^j – discrete operations performed by the operator in this mode.

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If you now set some time τ_i^j and τ_{refi}^j can serve as a basis for assessing the operator’s performance in terms of his performance. Considering that the quantitative assessment must lie within the normalized range [0,1], we introduce the value $t_{\max j}$ of the maximum time mismatch τ_i^j and τ_{refi}^j. As a result we have

$$I_{spj} = \quad (\tau_i^j - \tau_{refi}^j)/\ t_{max} \tag{10}$$

where – sign of timely execution of the j-th mode and =0, if, $(\ _i^j - \ _{refi}^j) \leqslant 0$ and $\delta_T = 1$, if $(\tau_i^j - \tau_{refi}^j) > 0$.

At the second level of the hierarchy, according to the accepted multi-level structure of the quantitative activity of the operator, a criterion of the form

$$J_j = \quad _{estj}I_{estj} + \ _{tenj}I_{tenj} + \ _{spj}I_{spj} \tag{11}$$

where I_{estj} I_{tenj}, I_{estj} – the amount of evaluation of the operator’s actions in terms of reliability and tension, speed, determined respectively by formulas (4), (6), (11), and $_{estj}$, $_{tenj}$, $_{spj}$ – coefficients of importance of parameters in the j-th mode, and

$$_{estj} + \ _{tenj} + \ _{spj} = 1 \tag{12}$$

Finally, at the top level of the hierarchy, a complex quantitative assessment is calculated for the entire educational task according to the empirical criterion developed and proposed by the authors in [10].

The training task consists of a certain set of test modes, hence the need to select the appropriate criterion for forming the resulting assessment of the operator for completing the entire training task (comprehensive assessment). For the comprehensive assessment to be unbiased and valid, the following conditions must be met:

– the maximum relative error of the total estimate must lie within the limits determined by the values of the maximum and minimum errors of the terms.

– the resulting assessment must take into account in some way the importance of each mode or group of similar modes.

The analysis showed that such conditions are satisfied by the empirical criterion of the form proposed in this article:

$$J_{task} = \sum_j^N (1/J_j)^{s_j^*} / \sum_j^N (1/J_j)^{s_j};\ s_j^* = s_j - 1;\ s_j \geqslant 1, \tag{13}$$

the value of which is determined on the basis of previously generated normalized estimates J_j for N modes, where j determines the serial number of the test mode.

By choosing a suitable value of s_j, you can make a targeted change in the criterion values in the range [0,1], taking into account the quality of execution of a particular mode, as well as the degree of its importance. Moreover, if all terms have the same (approximately the same) maximum relative error, then the sum also has the same (or approximately the same) maximum relative error. In other words, in this case the accuracy of the sum (in percentage) is not inferior to the accuracy of the terms. However, with a significant number of terms, the sum, as a rule, is much more accurate than the terms, since in this case mutual compensation of errors occurs, so the true error of the sum only in exceptional cases coincides with the maximum error or is close to it. This circumstance makes it possible to purposefully change the value of the complex criterion for monitoring and assessing the actions of NPP operators, taking into account the importance of individual modes of the training task.

Table 1.

Example of division of modes into groups

$J_1, J_3, J_6 \cdots \cdots$	$J_2, J_9, J_{11} \cdots$	$J_{N-3}, J_{N-1}, J_N \cdots$
1-*st* group	q-*st* group	R-*st* group

The number of permutations in which at least one of the private modes N gets from its own group to someone else's is determined as follows:

$$(P_0 = N! = \sum_{q=1}^{R} L_q)! \quad (14)$$

Thus N criteria J_j are divided into groups R according to the elements L_q in each partition group. It is known that the total number of permutations in this case will be equal to:

$$P_1 = \left(\sum_{q=1}^{R} L_q\right)! - \Pi_{q=1}^{R}\left(L_q\right)!. \quad (15)$$

In this case, the share of this number of permutations from the total number is determined as follows:

$$s = \frac{P_1}{P_0} = \frac{(\sum_{q=1}^{R} L_q)! - \Pi_{q=1}^{R}\left(L_q\right)!}{\sum_{q=1}^{R} L_q)!} \quad (16)$$

and can serve as the value of a discrete penalty step s_j, some j-th private mode, the assessment for which should be in the q-th group, is determined according to the expression:

$$s_j = 1 + (j - q) \quad s, if\ j \leq q, \quad (17)$$

$$s_j = 1, if\ j < q.$$

The quantitative values of the complex criterion obtained in this way (as well as the values of the evaluation criterion by mode) can be interpreted in a more acceptable scoring system. The scoring system is that the range of change of any variable, in this case criteria J_j, is divided into a number of intervals, each of which is assigned a score (point). Most often, interval scales are used for these purposes. In this, as in other scales, the basic rule of scales is observed, namely, the transformation of numerical values while maintaining unchanged the functions it performs. As a rule, the interval scale is entered up to linear transformation

$$\{x_i\} \rightarrow \{x_i{}^{|}\} = ax_i + b \quad (18)$$

and involves transforming scores obtained on one scale into scores on another scale using a linear transformation.

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Conclusion

To monitor and evaluate the activities of NPP operators during training on simulator complexes, it is proposed to present their work in the form of an initiative matrix, reflecting the sequential change in the current state of discrete controls on the NPP control panel and comparing them states with the states of the reference matrix of its activities, taking into account "forbidden" combinations of control states. An analysis of the professional activities of a nuclear power plant operator shows that his activities are quite accurately characterized by speed, error-free (reliability) and work intensity. The implementation of the three-level criterion for monitoring and evaluating the activities of nuclear power plant operators during training on simulator complexes proposed in this article is focused on the "expert-operator" scheme. By varying the execution time of the modes and the training task as a whole, it is possible to artificially create stressful situations for NPP operators and evaluate their actions.

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