An approach to quantifying the minimum reliability level of a ship nuclear power plant operator

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Abstract. The report proposes an approach to assessing the minimum reliability level of control panel operators of the ship nuclear power plants based on a combined probability-deterministic analytical-simulation method, functional-structural theory and probabilistic-algorithmic models of the ergatic systems functioning.

Introduction
At present, ship nuclear power plants (NPPs) are considered as complex technical open artificial systems of the ergatic (organizational and technical) class - the "human–machine" systems.

Analysis of the normative and technical documentation defining the main tactical and technical requirements for the reliability of ship NPPs and their systems showed that only the quantitative measures of non-ergatic (technical) elements such as NPPs, steam turbine plants, technical means control systems (CS) and an NPP as a whole are normalized. There are no such requirements for ergatic (biological) elements (personnel). This fact indicates that this issue has not been worked out well enough. Therefore, the proposed report focuses on the approach to quantifying the minimum reliability level of the NPP control panel operator.

1. The minimum level of operator reliability
From a systemic point of view, a ship NPP combines jointly operating elements: NPP technical means (TM); control systems and personnel (operator of the control panel). At the same time, two control channels can be distinguished in the scheme of this "human-machine" system functioning: remote and automatic (see Fig. 1) [1]:

- automatic control channel: NPP technical means → control devices → process control system → automatic control system → executive elements → NPP technical means;
- operator’s remote control channel: NPP technical means → control devices → process control system → information display facilities → human operator → control elements → remote control system → executive elements → NPP technical means.
The channel for automatic control of the ship NPP operation is used in the main operating modes: input, output and operation at power, testing algorithms for triggering emergency protection signals and warning signals with control. During the operation of the automatic circuit the operator is in a state of ergatic reserve, i.e. carries out redundancy of the automatic control system when it is unable to perform its functions for some reason.

The operator’s remote control channel is used, as a rule, when preparing a ship NPP for operation; carrying out maintenance; performing operations that are not included in the automatic control algorithms during input, output and operation at power of the NPP; redundancy of the automatic control system, as well as in other situations difficult to formalize.

The overall reliability of a ship NPP, as an ergatic system, depends on the reliability indicators of the system technical part (NPP technical means and control systems) and of the human operator.

Usually when applying the methods to quantify the reliability of the nuclear power plants the probability of failure-free operation of both the installation as a whole and its individual systems is determined in order to achieve the set goal of functioning [2]. The main measures are the reliability of technical elements (in our case, the NPP technical means and control systems) and the personnel (control panel operator) error-free actions. Therefore, the probability of the ship NPP failure-free operation \( P_{\text{ship NPP}}(t) \) is determined as a function:

\[
P_{\text{ship NPP}}(t) = f(P_{\text{tm}}(t), P_{\text{cs}}(t), P_{\text{h}}(t)),
\]

where:
- \( P_{\text{tm}}(t) \) – probability of failure-free operation of the NPP technical means;
- \( P_{\text{cs}}(t) \) – probability of failure-free operation of technical means control system;
- \( P_{\text{h}}(t) \) – probability of error-free operator actions;
- \( t \) – given interval of a ship NPP operation time.

As noted above, the analysis of the tactical and technical requirements for the reliability of ship nuclear power plants and their systems showed that minimum values were determined only for quantitative measures \( P_{\text{ship NPP}}(t) \), \( P_{\text{tm}}(t) \) and \( P_{\text{cs}}(t) \). The personnel \( (P_{\text{h}}(t)) \) in these documents are subject only to qualitative requirements to ensure the given reliability of the ship NPPs, its elements and systems operation. The main requirements are as follows:

- staffing and service organization must provide the necessary set reliability level of the daily technical means maintenance and the elimination of their sudden failures;
- qualifications, responsibility and discipline of all persons involved in the operation and maintenance of nuclear power plants must correspond to the complexity of nuclear technology and the requirements for ensuring its safety;
- high quality operator's performance measures in all control modes of a nuclear power plant are achieved by developing algorithms for solving specification and predicted emergency control tasks.
values of the probability that functionally independent operations will be performed without failure should be provided taking into account characteristics of operator interaction with the means of activity, i.e. control panel.

Therefore, as a normalizing quantitative measure of the ship NPP ergatic elements reliability, it is proposed to determine the minimum level of the operator reliability, by which we mean the minimum value of the error-free human operator action probability \( P_{\text{h}} \), at which the goal of the ship NPP operation is achieved with the required probability of failure-free operation \( P_{\text{ship NPP}} \) for a given time.

Thus, taking into account the requirements for minimum reliability values \( P_{\text{tm}} \), \( P_{\text{cs}} \) and \( P_{\text{h}} \), the expression (1) can be represented:

\[
P_{\text{ship NPP}}(t) = f(P_{\text{tm}}(t), P_{\text{cs}}(t), P_{\text{h}}(t)) \geq P_{\text{ship NPP}}^{\text{min}}(t)
\]

when \( P_{\text{tm}}(t) \geq P_{\text{tm}}^{\text{min}}(t), P_{\text{cs}}(t) \geq P_{\text{cs}}^{\text{min}}(t), P_{\text{h}}(t) \geq P_{\text{h}}^{\text{min}}(t), \)

where \( P_{\text{ship NPP}}^{\text{min}}(t) \) is the minimum required probability of failure-free ship NPP operation;

\( P_{\text{tm}}^{\text{min}}(t) \) – the minimum required probability of failure-free NPP technical means operation;

\( P_{\text{cs}}^{\text{min}}(t) \) – the minimum required probability of failure-free control systems operation;

\( P_{\text{h}}^{\text{min}}(t) \) – the minimum probability that a control panel operator acts without errors.

2. Quantifying the minimum level of operator reliability

Let us define \( P_{\text{h}}^{\text{min}}(t) \) when controlling the ship NPP operation, considering it as a system "operator - control systems - NPP technical means".

Using the methods of the functional-structural theory by A.I. Gubinsky [3, 4], an approach to formalizing the processes of ergatic systems functioning based on probabilistic-algorithmic models by V.M. Glushkov [4 p. 187, 5 p. 94] and the combined probabilistic-deterministic analytical-simulation method by G.A. Ershov [6, 7] with the graphic apparatus of functional integrity diagrams, we can represent a mathematical model of this system in the form of a tuple:

\[
\langle T, S, O, W, L \rangle \quad \text{when} \quad F = (T \cup S \cup O).
\]

where \( T \) - the set of elements (systems) of the ship NPP technical means with a given value of failure-free operation;

\( S \) - the set of elements (systems) of the technical means control system with a given value of failure-free operation;

\( O \) - the set of actions (operations, functions, programs) performed by the operator during control of the technical means with a given value of error-free execution;

\( L \) - the set of logical operators describing the dependencies of \( T, S, O \) elements operation;

\( F \) - the set of functional vertices;

\( W \) - the set of fictitious vertices;

Using (2) and (3) in the program complex BARS (8) we will develop models to quantify the reliability of the system "operator - control systems - NPP technical means" with automatic and remote control of the technical means based on simple and visual examples. At the same time, for convenience, let's assume that the values are:

\[
P_{\text{cs}}(t) = P_{\text{rc}} = P_{\text{ac}} = P_{\text{cs}},
\]

where \( P_{\text{rc}} \) - the value of the probability that the technical means remote control channel will work without failures;

\( P_{\text{ac}} \) - the value of the probability that the technical means automatic control channel will work without failures.
Graphical models (functional integrity schemes) will look like this: when the vehicle is remotely controlled by the operator, see Figure 2a; when the vehicle is automatically controlled and the operator is in an ergatic reserve see Figure 2b.

Fig. 2. Functional integrity schemes:

a) for remote control of the technical means by the operator; b) for automatic control of the technical means.

The models include the following random events:
1 - an event when technical means successfully perform their function, \( P_{tm}(t) = P_{tm} \);
2 - an event when the technical means automatic control channel successfully performs its function \( P_{ac}(t) = P_{ac} = P_{cs} \);
3 - an event when the remote technical means channel successfully performs its function \( P_{rc}(t) = P_{rc} = P_{cs} \);
4 - an event which consists in the failure-free execution of actions by the operator during remote control of technical means from the control panel, \( P_h(t) = P_h \).

The logical model of assessment of the system operation reliability in the case of remote control of technical means will be as follows:

\[ Y_S = y_5 = x_1 \cdot x_2 \cdot x_3 \]  

(5)

From (5) we obtain a probabilistic model:

\[ P_S = p_1 \cdot p_2 \cdot p_3 = P_{tm} \cdot P_{rc} \cdot P_h = P_{tm} \cdot P_{cs} \cdot P_h \]  

(6)

Taking into account (2) \( (P_S \geq P_{ship_{NPP}}) \) and (6), we determine the minimum reliability level of the operator functioning \( P_h^{min} \) for remote control of technical means:

\[ P_{tm} \cdot P_{cs} \cdot P_h^{min} \geq P_{ship_{NPP}} \]  

(7)

Note that with maximum values \( P_{tm} = P_{cs} = 1 \) the minimum reliability level of the operator \( P_h^{min} \) during the technical means remote control should be:

\[ P_h^{min} \geq P_{ship_{NPP}} \]  

(8)

The logical model of assessment of the system operation reliability in the case of automatic control of technical means and the operator being in an ergatic reserve will be as follows:

\[ Y_S = y_5 = x_1 \cdot x_2 \vee x_1 \cdot \overline{x}_2 \cdot x_3 \cdot x_4 \]  

(9)

From (9) we obtain a probabilistic model:
\[ P_S = p_1 \cdot p_2 + p_1 \cdot q_2 \cdot p_3 \cdot p_4 = P_{tm} \cdot P_{ac} + P_{tm} \cdot (1 - P_{ac}) \cdot P_{re} \cdot P_h \] (10)

Considering (2) \( P_S \geq P_{ship\_NPP}^{min} \) and (10), we define the minimum reliability level of the operator functioning \( P_h^{min} \) in automatic control of technical means:

\[ P_{tm} \cdot P_{cs} (1 + P_h^{min} (1 - P_{cs})) \geq P_{ship\_NPP}^{min} \]

\[ P_h^{min} \geq \frac{P_{ship\_NPP}^{min} - P_{tm} \cdot P_{cs}}{P_{tm} \cdot P_{cs} (1 - P_{cs})}, \text{ when } \frac{P_{ship\_NPP}^{min}}{1 - P_{cs}} - P_{tm} \cdot P_{cs} < P_{ship\_NPP}^{min}, \ P_{cs} < 1 \] (11)

Thus, having the values of \( P_{tm} \) and \( P_{cs} \), from (7) and (11), it is possible to determine the minimum probability value of the operator's error-free actions when technical means are remotely and automatically controlled, which would ensure the specified failure-free operation of the system "operator-CS-NPP TM" \( P_S \geq P_{ship\_NPP}^{min} \).

**Conclusion**

Standardization of operator reliability is important not only in the analysis of NPP reliability, but also in determining the level of training of specialists both in the process of their training and in the direct performance of professional activity tasks. The presented approach to quantitative assessment of the operator reliability (error-free) minimum level when performing algorithms for controlling the operation of a ship NPP will allow a more objective assessment of the human factor in the processes occurring in ergatic systems.

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