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METHODOLOGICAL COMPLEX FOR RESEARCHING THE FUNCTIONAL STABILITY OF PIPELINE TRANSPORTATION SYSTEMS

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The article presents studies on the functional stability of pipeline systems for supplying military forces with fuel. The conditions for the functional stability and its manifestation at various levels are defined and considered. A formation sequence of scientific foundations for the functional stability of pipeline systems at the methodological level is given. The essence of the proposed methodology for studying the stability of the functioning in various pipeline systems of oil products supply is explored.
Keywords: *pipeline system, research methodology, functional stability, system quality characteristics, reliability, fault tolerance, evaluation criteria*

New views on the conduct of special c*ampaign*s of the Armed Forces of the Russian Federation (AFRF) in the interests of ensuring the country's defense require the development of the organizational and technical generation of transport infrastructure for the supply of oil products to the military districts, including the advance creation of pipeline systems in the main strategic directions of forces actions using portable pipelines (PP), capable in times of war of ensuring the required functional stability of the complex technical system for the supply of oil products. The state of scientific developments in the field of pipeline technologies and the circumstances of increased interest in the study of their functional stability are explained by the following unresolved problems:

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1) a long pipeline length can lead to an increase in the proportion of technological disruptions to the system’s performance, a significant increase in costs arising from its long downtime, and, consequently, the scale of “damage” to the pipeline network;

2) in a large-scale pipeline network, the complexity and laboriousness of recovery operations increases; therefore, the desire to reduce the scope of its “damage” turns out, at the same time, to consist in the imperative to create more favorable conditions for restoring the required level of system functionality.

Solving these problems requires additional functional capacities from the created pipeline systems, which they may not possess if they have been designed for only normal operating conditions. In this regard, the urgency of substantiating scientific provisions in ensuring the stable functioning of pipeline systems becomes obvious. Such a substantiation requires the formation of a methodological complex of studies on the functional stability of pipelines in the logistics system (LS) of the AFRF.

The study of the functional stability of a pipeline system (as a complex technical system for providing fuel) involves the development of a set of principles and methods, constituting together the theoretical foundations of the functional stability of pipeline systems and the basis for the research data.

In order to study the functional stability of a pipeline system, it is necessary to form a methodological complex in stages involving interaction at three levels – methodological, modeling and assessment – in order to ensure the functional stability.

At the first level of the formation of a methodological complex for the functional stability of pipeline systems, the basic concepts and definitions of the studied condition are revealed, the assumptions in the study are stipulated, and the relationship with other system properties is assumed to be established allowing selection of the PP functional stability indicators. The level of methodological research also requires a solution to the problem of substantiating the functional stability characteristics of pipeline systems. The solution to this problem involves a consideration of all quality components determining the system’s functional stability and their integration into particular characteristics.

An important stage at the methodological level of studying the functional stability of a pipeline system includes the selection of its indicators having a relationship to the studied condition, taking into account both the efficiency of pipeline system application and the characteristics of its quality components. The methodological research level concludes with the choice of a system of criteria for the functional stability of the pipeline system, capable of solving a variety of synthetic problems affecting the stability of its functional subsystems.

The second level in the formation of a methodological complex of studies on the functional stability of a pipeline system involves solving generalized problems in modeling reliability and fault tolerance properties (synthesis of models) and the development of methods for quantitatively assessing its indicators. These methods are based on “mechanisms” for identifying the states of readiness and fitness of the pipeline system, taking into account an assessment of the feasibility for at least one to be realized under adverse effect conditions.

At the third level in the formation of a methodological complex of studies on the functional stability of pipeline systems, focused on the development of theoretical foundations for creating conditions for the stable functioning of various types of pipeline systems, including the formation of a system of provisions that determine the capability to control the condition, development and solution of optimization problems aimed at ensuring the maximum value of the functional stability indicator of pipeline systems, as well as problems related to the selection of the most preferable of possible options according to the criterion of functional stability.

When solving the assigned tasks, it is important to obtain estimates characterizing the evolution of the states of pipeline systems under specific adverse conditions, which requires such conditions to be standardized.

According to reliability theory, the “standard” conditions are those for which the system is designed. In fault tolerance theory, “standard” conditions are modeled (since they lie outside the limits of normal conditions). Provided that the models of “standard” conditions of reliability and fault tolerance are comparable, the results of assessing the functional stability of pipeline systems acquire scientific significance.

Focusing on the concept of the functional stability of pipeline systems, this condition in all cases can be found to connect the system with its abilities: resistance to environmental conditions; maintenance of their basic functional parameters; recovery of the established parameters, characteristics, and properties.

Thus, the concept of the functional stability of pipeline systems can be defined as the capability of the system to withstand conditions unforeseen by the regulations of normal operation, adverse effects that cause a change in the structure and algorithms of its functioning, and, at the same time, to maintain and/or restore the readiness and capability to perform its main functions to a given volume and during a given operating time. The essence of the functional stability of pipeline systems manifests itself in terms of the capability to maintain or restore the state of the capability and readiness of the system under adverse effect. The proposed definition fully combines the properties of reliability and fault tolerance of pipeline systems, ensuring, on the basis of the synthesis of these properties, the development of a methodological apparatus for assessing the functional stability of the PP in the armed forces LS.

Reliability, which characterizes the stable functionality of the pipeline system over the considered period of time, should be understood as the system property reflecting its readiness to continuously transport (pump) from the supplier to the consumer motor fuels and water at a given flow rate, in a given volume, and established quality, while maintaining the required technical characteristics.

For PPs operating under conditions of violations and losses, fault tolerance should be understood as the system property reflecting its capability to withstand the effects of weapons of destruction, to perform assigned tasks in case of partial damage, and to recover within a specified period of time. Therefore, the particular characteristics and indicators of fault tolerance must be determined taking into account the function specifics of PP operation.

The study of the pipeline system functional stability involves the quality and regularity of changes in the system under the influence of external and internal factors, taking into account its recovery capabilities. The term “quality” should here be understood not in a broad, but in a narrow sense (whether it ensures the operable state of the pipeline system or not). The generality of the study of the functional stability and the similarity of the conditions, under which the quality of the pipeline system is investigated in the theory of reliability and fault tolerance, determines the need to identify the unity of the fields of study of these scientific disciplines.

Let us assume that the quality of the pipeline system is characterized by the $K(k_1, k_2, \ldots, k_m)$ vector of parameters with the values changing under the influence of the environment (they are random and forecasted at the level of probabilistic models). Let K_{NTD} be the vector of the parameters of the pipeline system, characterizing its state that meets the requirements of NTD. In the event that, for some reason, the quality parameters of the pipeline system change so that $K < K_{\mathrm{NTD}}$, the system degrades, i.e., loses quality. At the same time, the processes accompanied by a change in quality, from $K_{\mathrm{NTD}} \in K$ to $K \in K_{\mathrm{NTD}}$, can proceed both under design and off-design conditions. Under design conditions, changes are the result of failures, while, under off-design conditions, they are the result of damage to the elements of the pipeline system. Thus, in the first case, the study of the regularities associated with the analysis of the operability of the pipeline system is carried out in terms of reliability, while in the second it is conducted in terms of fault tolerance. The study of the dynamics of changes in the quality of the pipeline system in the area $K < K_{\mathrm{NTD}}$ concerns the states of readiness and the capability of the system to stable functioning. The quality components of the pipeline system at various hierarchical levels are schematically shown in Fig. 1.

When modeling the states of readiness and capabilities of pipeline systems to support stable functionality, the technique of calculating probabilistic functions has much in common with reliability and fault tolerance indicators. Here, the physical meaning of the reliability property is close to that of fault tolerance. The difference lies in the fact that the latter is assessed under conditions of external influences leading to failures of elements due to their damage. Damage models of system elements are based on a comparison of the parameters, characterizing the calculated design resistance of pipeline systems to failures and their protection with the parameters of the external influence model of damaging factors (under conditions of uncertainty) adopted as standard.

Thus, the stability of the pipeline system functionality can be investigated on generalized models of reliability and fault tolerance (i.e., using the model synthesis apparatus). Solving the problem of synthesizing reliability and fault tolerance models with substantiation of the functional stability characteristics of the pipeline system presupposes the integration of all system quality components into particular characteristics, thus determining operational efficiency.

The analysis of manifestation of the stable functioning condition at the "upper" level involves considering the structure of the success indicator of the pipeline system functionality, i.e., the efficiency of its use, possible to be represented by the expression

$$E = \left\{Y; N; R; S_{a.e.} \leftrightarrow S_p; H_{\mathrm{n}} \leftrightarrow H_{\mathrm{p}}\right\} \tag{1}$$

where Y is a set of parameters characterizing the operational conditions of the pipeline system; N is a set of parameters characterizing the physical nature of the adverse effect; R is a set of parameters characterizing the readiness of the pipeline system to complete the set task; $S_{a.e.}$ is a set of parameters determining the implemented ways of using the pipeline system under various adverse effects; S_p is a set of parameters that determine the possible ways of using the pipeline system for its intended purpose, allowing it to complete the task with a probability not less than stated (P_{set}); $P_{a.e.}$ is a set of characteristics of the pipeline system's purpose implemented

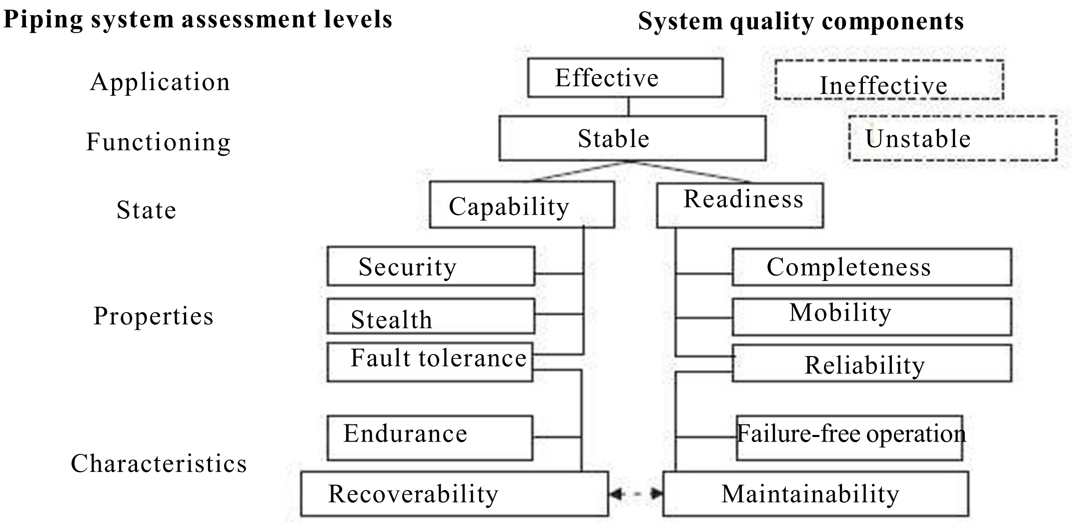

Fig. 1. Quality components of the pipeline system.

under adverse effects; P_p is a set of characteristics of the pipeline system purpose, necessary to complete the task with a probability not less than stated (P_{set}).

The combination of conditions $P_p \subset P_{a.e.}$ and $S_p \subset S_{a.e.}$ can be considered as a suitability criterion in the process of identifying the capability states of a pipeline system. If the suitability criterion is met, then $\{P_p, S_p\} = A$ (where A is a set of parameters that determine the capability of the pipeline system to effectively complete the task). Then expression (1) takes the form

$$E = E\ \{Y, N, R, A\}. \tag{2}$$

In order to obtain comparability of functional stability estimates, it is necessary to standardize the operational conditions (Y) of the pipeline system, as well as to standardize the model of external influence (reaction). If such a standardization is assumed to be completed, then expression (2) can be written in the form

$$E = E\ \{R, C\}. \tag{3}$$

This means that the success of the pipeline system functionality (the efficiency of its use) is determined by the achieved levels of readiness (R) and capability (C) of the system, i.e., the realization of its inherent potential under the given conditions. Then, from the position of the "upper" level of assessing the quality of the pipeline system, the functional stability indicator (FS) will be an estimate of the chances of keeping the system in two main states (readiness and capability):

$$FS = \begin{cases} FS\{\mathrm{R}\} \\ FS\{C\} \end{cases} \tag{4}$$

According to the analysis of Fig. 1 and the above reasoning, the set of a pipeline system properties sufficiently determines its state to confirm that its functional stability can be linked both heuristically (in the course of logical reasoning) and analytically (in the course of modeling) with the readiness (R) and the capability (C) states of the system. This conclusion appears to be in good agreement with the definition of the functional stability of the pipeline system.

In order to model the system quality analysis "from below" (from the quality characteristics of the system), it is necessary to understand the mechanism of the influence of the functional stability on these pipeline system states. In order to do this, let us make an assumption about the independence of the constituent properties of the functional stability of pipeline systems and the possibility of their separate assessment.

The acceptability of such an assumption in relation to fault tolerance is justified by this property manifesting itself only when, under the influence of damaging factors, the elements of the pipeline systems lose their capability to resist them, i.e., are destroyed. This condition assumes such properties as stealth and security of system elements to be absent or latent.

The acceptability of the assumption regarding reliability is substantiated by this property only being manifested when the elements of pipeline systems, having accumulated failures under excess perturbation, cause the system to lose its operational integrity. This condition assumes such properties as mobility and completeness, determining the readiness of pipeline systems to some extent to be absent or have their purpose unfulfilled.

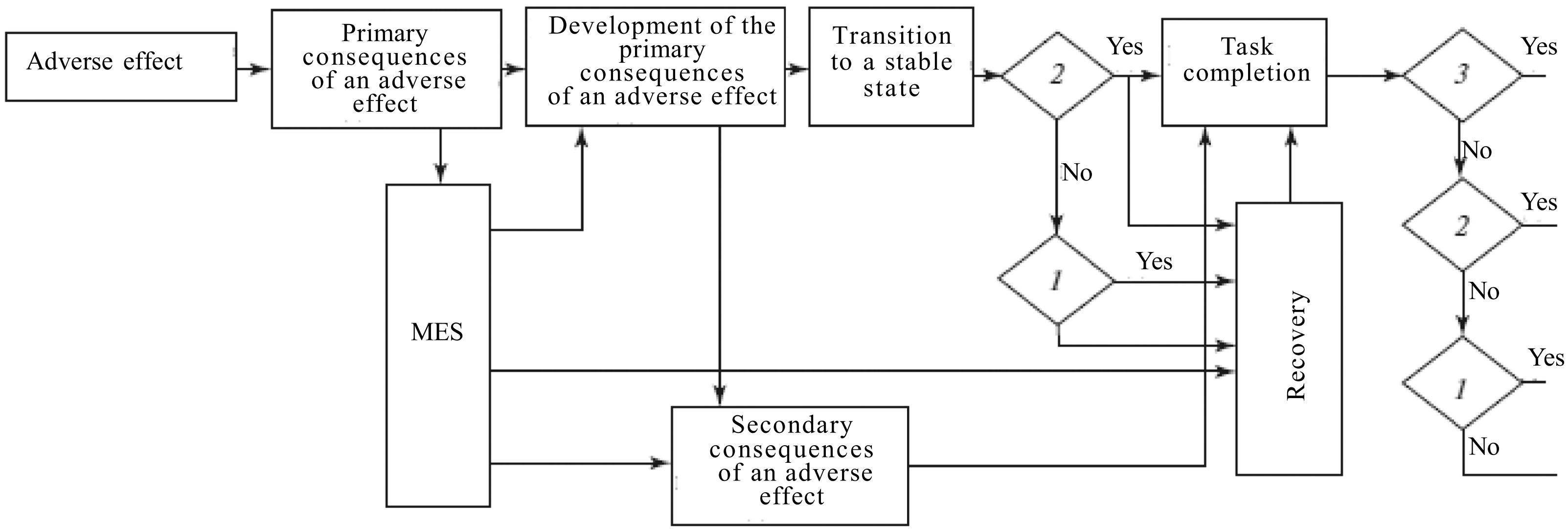

Fig. 2. State evolution of the pipeline system after an adverse effect: 1) accident, 2) operable state, 3) task completion.

Taking into account the definition of the conditions for stable functioning and these assumptions, fault tolerance and reliability can be monitored comprehensively according to the condition: has the pipeline system retained states of capability and readiness? Additionally, it becomes possible to simulate the studied condition (development of an analytical apparatus for determining the real state of the pipeline system after an adverse effect).

In order to justify the choice of models for the functional stability of the pipeline system, it is necessary to consider the behavior of the system following an adverse effect. In a formalized form, such a behavior of the pipeline system is shown in Fig. 2. As a result of an adverse effect, primary consequences arise in the system as expressed in the disruption of operability elements or functional connections, as well as in the distortion of functioning algorithms. Information about the primary consequences of an adverse effect is sent to the means of ensuring the stability (MES) of the system's functioning, including means of monitoring operability, emergency protection, reconfiguration, and control. The main task of MES is to have time to work out its algorithms and perform the necessary compensatory actions even before failures begin to appear in the pipeline system.

The action of the MES influences the development of the primary consequences; depending on the intensity of the processes in the pipeline system and the specific external conditions of functioning, the system ultimately goes into one of the possible stable states. After the transition to a new state, it is advisable to assess the primary consequences resulting from the attribution of the pipeline system state to one of three classes: operable, inoperative (non-emergency), emergency. Based on the results of the proposed classification, it is advisable to assess the functional stability of the PP according to the evolution of the system elements (when the elements are in an operable state, the system returns to the task completion).

If the state is inoperative, the pipeline system may return to the task completion following some recovery procedures. The transition of the pipeline system to a new stable state does not end the endeavor for stability, since, during further functioning until the assigned task is completed, secondary consequences from an adverse effect may appear; these may be more distant, but no less dangerous than the primary consequences associated with various uncontrollable or poorly controlled physical processes. The development rate of secondary consequences and their ultimate result also significantly depend on the work of the MES. After a certain set time, the results of the completion of a task by a system should be assessed according to four possible outcomes.

In the process of the endeavor to maintain the functional stability of the pipeline system, two stages can be distinguished: for maintaining operability and for the successful completion of the task, despite the primary and secondary consequences of an adverse effect. At the same time, two tasks are distinguished: assessment and ensuring functional stability. This general scheme fits the evolution trajectories of a pipeline system with adverse consequences of varying intensity and severity.

Here, the development processes of the consequences of the adverse effect play an essential role. At the same time, the endeavor to maintain the functional stability of the pipeline system proceeds in time, while the severity of the consequences, as well as the state and ultimate fate of the system, is largely determined by the capabilities of the MES and their readiness for effective use. The availability of a speed margin at the MES creates conditions for timely decision-making, which results in a limitation of the secondary consequences of an adverse effect to preserve the operability of the pipeline system, albeit with somewhat reduced operational characteristics. As soon as the means of endeavoring to preserve the functional stability of the pipeline system have an impact on the recovery processes, its final state can be established according to the characteristics of the system properties.

The functional stability indicators of the system are advisable to be estimated using analytical methods. If only the direct consequences of an adverse effect are important, then the levels of operability and functioning are assessed immediately after the termination of the adverse effect. Here, the functional stability of the pipeline system is appropriate to be assessed by its state.

For a pipeline system, the specified functions are performed within a certain time interval following the end of the adverse effect. The success in the task completion is determined by the state of the system at the initial moment and the trajectory of functioning in the future. Here, other factors begin to influence (the readiness of the pipeline system elements, the efficiency of the recovery subsystems, etc.). In this case, the functional stability is assessed by the results of the task completion.

Success in the synthesis of models for assessing the functional stability of a pipeline system is achieved by integrating a wide range of particular models for various purposes using deterministic and probabilistic methods to describe the processes of operability. The variety of particular models for assessing the functional stability of the pipeline system is shown in Fig. 3.

The model of adverse effects describes the areas of its action.

The model of functional-algorithmic structure describes the functionality of the pipeline system elements, the routes of energy flows, as well as the functional and structural hierarchy of its subsystems.

The physical process model is used to analyze the transients in a pipeline system following an adverse effect. It describes the trajectories of the functioning process.

The model of primary consequences of an adverse effect is obtained by interacting a physical process model with an adverse effect model. Perturbations associated with an adverse effect, arising under the influence of perturbations and introduced into the model of physical processes and transient processes, are considered.

The model for ensuring the means of stability contains information about the readiness and capability of system elements to withstand adverse effects. The algorithms for making decisions about the endeavor to maintain functional stability included in the model form control actions are aimed at using the reserves created for operation in extreme situations.

The model of development of primary consequences is derived from a combination of primary consequences of adverse effect and means of ensuring stability models, promoting for obtaining the trajectory of the transition process taking into account the actions of the means of ensuring stability. This model is aimed at determining a new state of stable functioning of the pipeline system.

The model for the synthesis of reliability and fault tolerance contains information about the readiness and capability of the pipeline system to complete the task, the influence of adverse effects on the level of the system’s operability, the response to failures and damage to its elements. This model is aimed at assessing the functional stability of the pipeline system based on the results of the task completion.

The model of secondary consequences of an adverse effect reflects those consequences arising in the pipeline system due to a reduction in the scope of functions performed and a deterioration in technical characteristics. These include consequences that lead to a reduction in the reserves remaining after the adverse effect, an increase in the time of performing the functions of the pipeline system, and an increased consumption of materials for performing functions.

The recovery model contains a description of emergency resources and methods for restoring the functional and algorithmic structure of the system component engaged in task completion.

The task completion process model is obtained as a result of the synthesis of five models: functional and algorithmic structure, physical processes, synthesis of reliability and fault tolerance, recovery, and secondary consequences. The synthesis of these models ensures the assessment of the functional stability according to the results of the task completion.

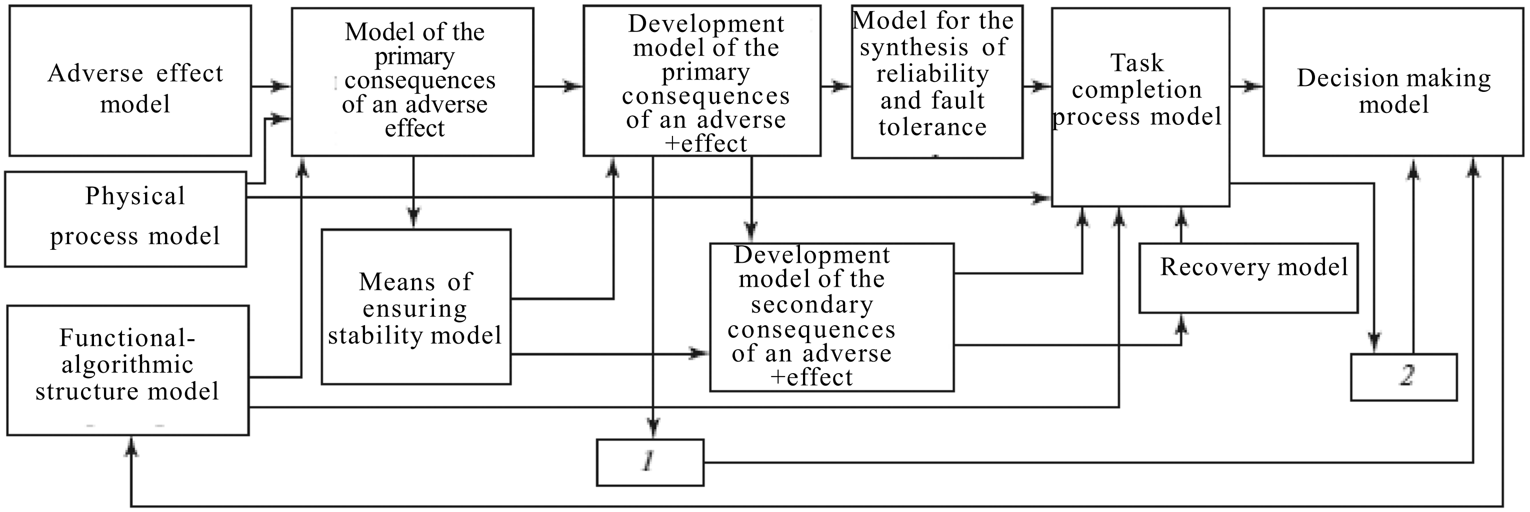

Fig. 3. Structural models for assessing the functional stability of the pipeline system: 1) assessment of the functional stability according to the state of the system, 2) assessment of the functional stability according to the results of the task completion.

The decision-making model provides the designer with advice on changing the structure and parameters of the pipeline system, as well as the additional development of means for ensuring stability if evaluations show an unsatisfactory level of the system's functional stability.

The functional stability of the pipeline system can be assessed by synthesizing the above models forming its structure.

The revealed interrelationships between the conditions of stable functioning of the pipeline system and the properties of reliability and fault tolerance allow the characteristics of the system's functional stability to be selected from the standpoint of reliability and fault tolerance. In addition, they can be used to evaluate its functionality in terms of readiness and capability states.

In order to assess the functioning process of the pipeline system, let us use a mathematical model characterizing its operability or a state of failure at any arbitrary moment of time (*t*).

Let us consider the entire process of the pipeline system functionality as an alternating sequence of random variables t_1, τ_1, ..., t_i, τ_i, (t_i is the duration of *i*-th period of non-failure operation of the pipeline system ($i = 1, 2, ...$); τ_i is the duration of *i*-th period of downtime of the pipeline system).

Thus, the condition is obtained

$$X(t,\tau) = \begin{cases} X \; if \; t \in t_i \\ \bar{X} \; if \; t \in \tau_i \end{cases} \tag{5}$$

where $X(t, \tau)$, X, and $\bar{X}$ are the states of the pipeline system (current, failure-free, and failure, respectively).

Let us consider the process of a pipeline system functionality from the standpoint of reliability as a system consisting of *n* elements. Then the state of the pipeline system at the moment in time *t* will be determined by the state of its individual elements at this moment [1]:

$$X_{pl}(t,\tau) = \Phi\{X_1(t,\tau), X_2(t,\tau), ..., X_n(t,\tau)\} \tag{6}$$

where $X_n(t, \tau)$ is the current state of *n*-th element of pipeline systems.

Probabilistic models (5) and (6) show that the functional stability of a pipeline system is determined by the reliability of its elements, with the combinations of states corresponding to a failure-free or failure state of the system as a whole.

In our opinion, it is advisable to evaluate the stable operation of the pipeline system by combining two reliability characteristics determining the state of the system's readiness – reliability and maintainability.

As reliability indicators of the pipeline system, the following are selected: probability of failure-free operation, *i.e.*, the probability that a failure of a pipeline system element will not occur in a given time interval; failure rate, *i.e.*, the conditional density of the failure probability for an element of the pipeline system, determined for the considered moment in time, provided that no failure has occurred before this moment.

As maintainability indicators of the pipeline system, the following are selected: the probability of recovery during a given time interval, *i.e.*, the probability that the time of recovery of the system's operability will not exceed a given one; the recovery rate of the system, i.e., the conditional density of the probability of operability recovery for the element of the pipeline system, determined for the considered moment in time provided that, up to this moment in time, the element of the pipeline system was in a state of failure.

Let the readiness factor be a comprehensive indicator of the state of readiness of a pipeline system characterizing the stability of its functionality.

The failure flow parameter (λ_f), referring to the average number of failures of an element of the pipeline system per unit of time, is determined through the average operating time between two of its successive failures (mean time between failures – $t_{f_{av}}$):

$$\lambda_f = 1/t_{f_{av}} \tag{7}$$

Mean recovery time ($\tau_{f_{av}}$) is the average time of the forced downtime of a pipeline system element resulting from identifying and eliminating a failure.

The reciprocal of $\tau_{f_{av}}$ is represented by the intensity of its recovery:

$$\mu_f = 1/\tau_{f_{av}} \tag{8}$$

Indicators of τ_f and μ_f characterize the recoverability of an element of the pipeline system.

The probability that, at any moment of time, an element of the pipeline system is in an operative condition is characterized by the coefficient of its readiness:

$$K_{f_{ar}} = \frac{t_{f_{av}}}{t_{f_{av}} + \tau_{f_{av}}} \tag{9}$$

For the pipeline system as a whole, quantitative indicators of reliability comprise:

- the parameter of the total flow of independent failures of pipeline system elements (λ_{f_i}):

$$\lambda_T = \sum_{i=1}^{n} \lambda_{f_i} \tag{10}$$

n is the number of elements making up the pipeline system;

- mean recovery time of the constituent elements of the pipeline system ($\tau_{mean\ pl}$):

$$\tau_{av_T} = \frac{1}{\lambda_T} \sum_{i=1}^{n} \lambda_{f_{i_{av}}} \tau_{f_{i_{av}}} \tag{11}$$

- coefficient of readiness of the pipeline system for stable operation (K_r):

$$K_r = \frac{1}{1 + \sum_{i=1}^{n} \lambda_{f_{i_{av}}} \tau_{f_{i_{av}}}} \tag{12}$$

In assessing the fault tolerance of a pipeline system, the laws of occurrence and distribution of failure of system elements differ from those used in the theory of reliability. Therefore, it is proposed that the study of the functional stability of the pipeline system from the standpoint of fault tolerance be carried out on the basis of the following characteristics arising from the specifics of the operation of the pipeline system, comprising the resistance of the main elements of the system to the impact of the counter forces and the capability of the system to complete the specified task when its elements are damaged.

The fault tolerance characteristics proposed for the study on the functional stability of the pipeline system are qualitative in nature. For a generalized assessment of their effect on the fault tolerance of the system and the choice of optimal solutions to ensure the stability of its operation, it is advisable to obtain an optimization indicator of fault tolerance, reflecting the ratio of the probable transport work of the pipeline system per campaign to the technically possible transport work.

In order to assess the fault tolerance of the pipeline system, let us use the complex indicator of its fault tolerance coefficient (K_{surv}), which characterizes the decrease in the transport work of the pipeline system as a result of the impact of enemy weapons [2]:

$$K_{surv} = W_{act} / W_{plan} \tag{13}$$

where W_{act} is the actually performed transport work per campaign; W_{plan} is the technically possible (planned) transport work of the pipeline system.

Let us assume that the capability of the pipeline system to complete the specified task will largely depend on the presence of free (filled) capacity of intermediate reservoir groups (IRG) at the junction of sections of the pipeline system, ensuring stable operation of the system in the event of damage to the previous (or subsequent) sections.

In order to assess the capability of the pipeline system to the task completion, let us justify the need for IRG presence. If the pipeline system consists of successively interconnected sections, then

$$W_{act} = W_{act_1} + W_{act_2} + \ldots + W_{act_n} \tag{14}$$

where W_{act_n} is the actually performed transport work of the n-th section per campaign.

In the event of damage to one or more sections, the transport work performed by the pipeline system will be determined by the expression

$$W_{act} = W_{UD} + W_D \tag{15}$$

where W_{UD}, W_D is the actually performed transport work for an operation on the undamaged and damaged sections of pipeline system, respectively.

Then the system fault tolerance coefficient is determined by the expression:

$$K_{surv} = \left(W_{UD} + W_D\right) / W_{plan} \tag{16}$$

Now, it is necessary to consider cases of damage to sections of the pipeline system.

Depending on the capacity of the IRG, the actually performed transport work for the campaign in the sections with undamaged linear part will be determined by the following relationship:

$$W_{UD} = QL_{UD}\left[t_{calc} - \left(t_{rec} l - \frac{V_{IRG}}{Q_0}\right)\right] t_{\Sigma} \tag{17}$$

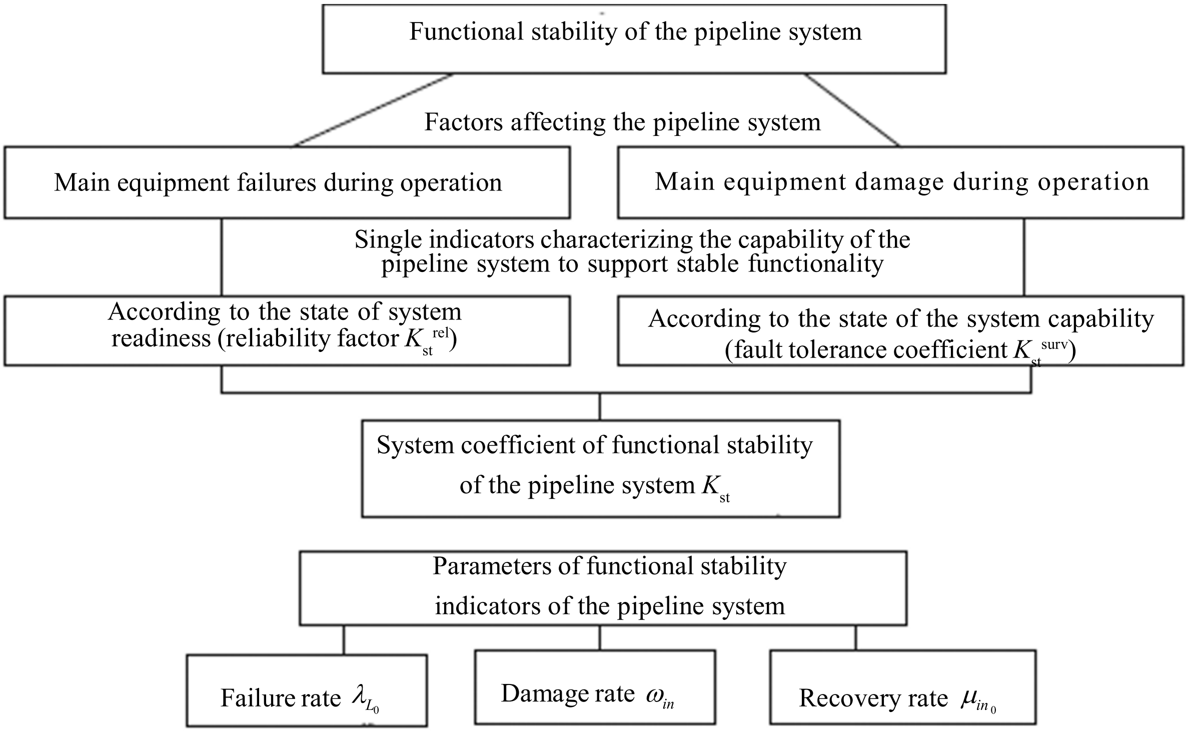

Fig. 4. Functional stability indicators of the pipeline system and the parameters of their assessment from the standpoint of reliability and fault tolerance.

where Q_0 is the estimated pumping capacity through the pipeline, m^3/h; L_{UD} is the total length of the undamaged sections, m; t_{calc} is the calculated operating time of the pipeline system per day, h; V_{IRG} is the capacity of IRG, m^3; t_Σ is the duration of work on the delivery of fuel per campaign, days; t_{rec} is the recovery time of 1 km of the pipeline system, h; l is the number of kilometers of the damaged pipeline.

The actually performed transport work for the campaign in the sections with damaged linear part will be determined by the following relationship:

$$W_D = Q_0 L_D \left(t_{calc} - t_{rec} l\right) t_\Sigma \tag{18}$$

The planned transport work of the pipeline system is determined from the expression

$$W_{UD} = Q_0 L_0 t_{calc} t_\Sigma \tag{19}$$

where L_0 is the total length of the pipeline.

After substituting expressions (17), (18), and (19) into formula (16), we obtain a formula for determining the complex indicator of the pipeline system fault tolerance depending on the length of the damaged area and the the IRG capacity (at $V_{\mathrm{IRG}}Q_0t_{\mathrm{rec}}l$):

$$K_{surv}^{lp} = \frac{L_{UD}\left(t_{calc} - t_{rec}l + \dfrac{V_{IRG}}{Q_0}\right) + L_D(t_{calc} - t_{rec}l)}{L_0 t_{calc}} \tag{20}$$

The identified relationships allow the functional stability indicators of the pipeline system to be selected from the standpoint of its reliability and fault tolerance (Fig.4).

The systemic indicator of functional stability (K) at various levels of assessing the quality of the pipeline system comprises a quantitative measure of the chances of the system maintaining its state of capability and readiness following the adverse effect of perturbation factors on its elements.

The K_{st} system index can be calculated as the product of single indicators of the functional stability for the subsystems of the pipeline system, provided that the disturbing factors arise.

The single indicators of the functional stability of the pipeline system include:

a) fault tolerance coefficient (K_{st}^{surv}) characterizing the "dynamics" of maintaining of the state of capability by the pipeline system at x-fold adverse effect (the acting disturbance factor x = 1, 2, ...);

b) reliability coefficient (K_{st}^{rel}) characterizing the "dynamics" of the system maintaining the state of readiness when the elements of the pipeline system accumulate failures after an x-fold adverse effect on them.

In this case, the probability of the pipeline system being in a state of stable functioning can be determined by the formula

$$P(K_{st}) = \prod_{i=1}^{k} P\left(K_{st_i}\right) \tag{21}$$

where K_{st_i} are single indicators of the functional stability of the pipeline system (from the standpoint of reliability K_{st}^{rel} and fault tolerance K_{st}^{surv} , respectively).

Parameters of stable functioning indicators include the rates of: damage (when assessing fault tolerance – ω_{in}); failures (when assessing reliability – λ_i); and recovery (when assessing fault tolerance and reliability – μ_{in_0}) of the pipeline system elements. Parameters of ω_i , λ_i , and μ_{in_0} indicators are calculated in accordance with work [3].

The following can be selected as distinctive features (criteria) for assessing the stable functioning of the pipeline system:

a) the criterion of suitability [4] represented by the ratio

$$FS \geq FS_{set} \tag{22}$$

where FS_{set} is the set value of the functional stability indicator of the pipeline system.

The scope of the suitability criterion involves a substantiation of the requirements for the pipeline system, taking into account the given level of system functional stability;

b) the criterion of optimality [4] characterized by the expression

$$FS = FS_{\max} \tag{23}$$

This criterion allows the formation of a vector of pipeline system parameters at which the indicator of functional stability is maximal. The scope of the criterion is determined by the design problem provided that, within the given constraints, the indicator has a maximum value.

For a *PP*, the most informative criterion for the functional stability is the system criterion comprehensively taking into account the influence of external and internal factors determining the efficiency level of the pipeline system. In terms of this criterion, the expected value (mean value) of the supply through the *PP* over a long time interval can be applied, since the current pumping capacity through the pipeline (Q_i) is a probabilistic value depending on the state of the pipeline system, which differs from the calculated one (Q_{av}) due to technical failures and damage to *PP* elements.

During operation, the pipeline system can be in one of three possible states:

I – the state of full (calculated) performance, corresponding to the full operability of all basic elements of the system;

II – the state of temporary incomplete (partial) performance, corresponding to the failure of one or more intermediate pumping stations;

III – the downtime state with zero-pumping performance through the pipeline corresponding to the failure of the main elements of the pipeline system (failure or damage to the linear part of the *PP*, the initial pumping station, destruction of the *IRG*).

Considering that the probabilities of the performance states of the pipeline system can be calculated by mathematical models using the methods of the dynamics of means [3], for all states of the system, it is possible to write

$$Q_{av} = \sum_{i=1}^{m} Q_i P_i \tag{24}$$

where Q_i is the performance of the pipeline system in the i-th state; P_i is the probability of i-th state of the system; i is the number of the pipeline system state, characterized by the corresponding value of performance; m is the number of possible system states.

Dividing the left and right sides in expression (24) by the calculated capacity (Q_0) and entering the designations of $K_i = Q_i/Q_0$ (performance decrease coefficient of the pipeline in i-th state), we get

$$K_{UT} = \sum_{i=1}^{m} P_i K_i \tag{25}$$

where K_{UT} is the average utilization rate of the pipeline system, numerically equal to the mean probability of the system reaching the rated nominal performance and calculated as the expected value of a random variable.

The values of the state probabilities (P_i) can be obtained by modeling the operation of pipeline systems according to the scheme of Markov random processes [5] ensuring the assessment of the level of *PP* functional stability in the logistics system.

REFERENCES

1. GOST 27. 001-95. Reliability in Equipment. Collection of State Standards [in Russian].
2. P.K. Germanovich, *Fault tolerance of Field Main Pipelines in Contemporary Military Campaigns* [in Russian], UVVTU, Ulyanovsk (1998).

3. V.A. Abchuk, F.A. Matveichuk, and L.P. Tomashevskii, *Handbook of Military Campaign Research* [in Russian], Voenizdat, Moscow (1979).
4. Yu.I. Stekol'nikov*, Fault tolerance of Systems* [in Russian], Politekhnika, St. Petersburg (2002).
5. Yu.N. Pirogov*, Mathematical Modeling of the Functioning Processes for Objects and Technical Means of Providing Fuel* [in Russian], Neografiya, Moscow (2006).