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INFORMATION SYSTEM OF THE DIAGNOSTICS OF A FUNCTIONAL RELIABILITY OF PIPELINE SYSTEMS

The information system of the diagnostics of the reliability of pipeline systems is developed in the paper. It is intended to provide a single information space for prompt and coordinated support of management decisions in the workplaces of technical specialists and repair personnel of structural subdivisions of a pipeline system. The task of minimizing costs is formulated, which is solved by numerical optimization methods and the graphical method. The information system makes accessible comparative analyses of alternative structures of a pipeline network by criterion of functional reliability.

Keywords: *information system, diagnostics, model, reliability, pipeline system.*

Problem statement

Pressure pipeline transport has a significant role in the economy of Ukraine. Increased requirements are applied to the reliability of pipeline systems in terms of economic costs, industrial and environmental safety. The breach of the pipeline leads to significant environmental pollution and substantial economic losses. High working pressure, huge masses of pumped products, significant effects of physical and climatic conditions of the environment lead to gradual wear and tear, and therefore to failures and increased risk of technological disasters. Accordingly, the problem of developing of information system of the diagnostics of functional reliability (ISFR) of pipeline systems is relevant.

Analysis of recent research and publications

The problem of reliability is controversial for all actors related to the pipeline system [1]. On the one hand, producers and consumers of the end product want the pipeline system to be reliable. But, and on the other hand, consumers want transport services to be cheap. Operators, on the one hand, seek to ensure the reliability of the system at the appropriate level in the future. On the other hand, they seek to devote as little financial, material and labor resources as possible to achieve and maintain this level. The elimination of contradictions can be achieved only by finding a compromise value of the current reliability, which would satisfy all actors in the system equally. In this situation, to successfully solve the problem it is necessary to have a reliable method of creation mathematical models to calculate the functional reliability of pipeline transport systems. Existing methods of calculating the reliability of pipeline networks are focused on calculating the indicators that characterize their technical condition [2, 3] or the accuracy of the hydraulic calculation regarding the delivery and distribution of the end product [4]. The issues of functional reliability of pipeline networks are either not considered at all, or concern only its assessment [5].

Problems of reliability of pipeline systems

Among the indicators of reliability of pipeline systems can be highlighted two main indicators that affect the functioning of the pipeline system and which are called functional reliability:

– maintainability, which determines the property of the system to continuously transport the end product to consumers during maintenance work for the purpose of to restoring the technical reliability of the structural elements of the system, which they lose during long-term operation due to wear or aging;

– the probability of uninterrupted supply of the target product to an individual consumer or group of consumers over a period of time, which determines the objective ability of the system to conform to its purpose.

Improving the functional reliability of pressure pipeline transport systems (PPTS) is one of the most important tasks facing operators. All subjects of the transportation system are interested in its solution. Existing structural methods to increase the reliability, such as redundancy and installation of bridges, will be discussed in this article. To compare the influence of the network structure on its functional reliability, the analytical method of emergency repair zones (ERZ) is used.

The structure of PPTS significantly affects the indicators of functional reliability, which means the ability of the system to solve its main task – to continuously transport the end product to the consumer. Among PPTS with equal technical parameters of pipelines, the highest functional reliability is possessed by those whose structure provides a large number of alternative routes of the end product transportation from sources to each consumer. However, the length of transport routes has a negative effect on the functional reliability of the system: the longer the route, the lower the reliability.

Identifying and inclusion the dependence of the functional reliability of the system on its structure plays an important role in the design, operation and development PPTS. To successfully solve the problems of PPTS design, rational operation and choosing of the best option for the development of existing PPTS, it is necessary to have a method of functional reliability calculating, which would allow to calculate the probability of continuous transportation of the end product from source to consumer with high adequacy. The calculation method should include both the length of the pipelines and any feature of the structure of the pipeline system that affects the required functional reliability.

Pipeline transport network is the most important and most complex part of PPTS, which carries out transportation and distribution of the end product. Practically, the calculation of the functional reliability of the pipeline transport system is limited to the calculation of the functional reliability of the distribution pipeline network.

The PPTS reliability is set at the design stage and maintained at the stage of construction and commissioning. Over the years, however, the reliability of individual structural elements decreases, that leads to a need for rapid diagnosis of the reliability of PPTS in order to make appropriate management decisions and measures to maintain reliability at a given level. This can be achieved only by developing an information system that collects data on the state of individual elements of PPTS and the functional reliability calculation, using appropriate methods and models. In the general case, such an information system will be a subsystem of the automated control system of the whole PPTS.

Functional structure of ISFR

Based on the general principles of the information systems creation [6], the following functional scheme of the information system of functional reliability analysis PPTS is proposed (Fig. 1).

ISFR should be a subsystem of the automated process control system of the whole PPTS.

The main objectives of the creation of ISFR are:

– monitoring and forecasting the technical condition of the pipeline as a whole and its elements;

– pipeline resource monitoring and monitoring of reservoir parks;

– planning and control of current, average and capital repairs.

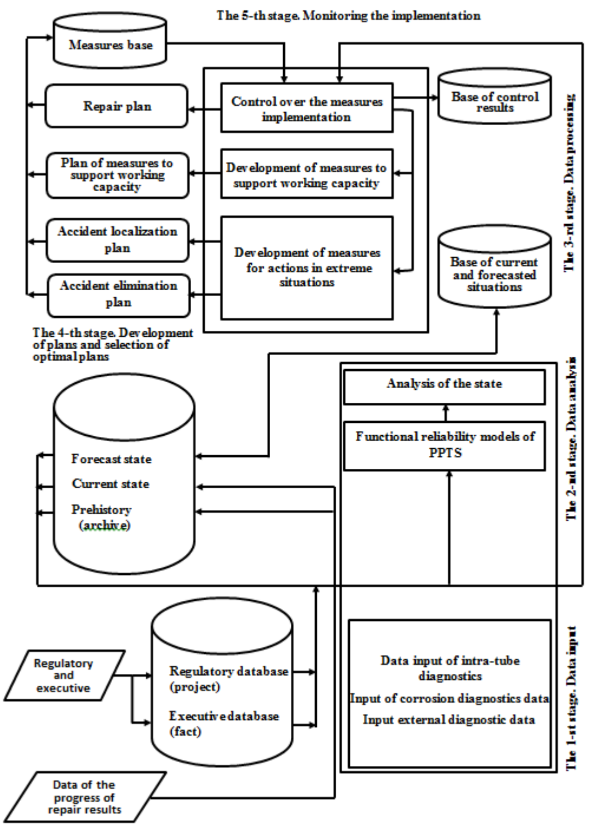

Fig. 1. Functional scheme of ISFR

The actual basis for implementation of ISFR is:

– executive documentation;

– factory catalogs and technical passports of the equipment;

– retrospective statistical material;

– experience of operation of the existing pipeline;

– information that comes from control sensors installed at critical points of the pipeline network.

ISFR is intended to provide a single information space for prompt and coordinated support of management decisions in the workplaces of technical specialists and repair personnel of structural subdivisions of PPTS.

Since the process control system of a pipeline system is generally a multilevel system, the functional structure of ISFR is considered as a system to support management decisions at each level of management.

It involves the implementation of a sequence of such steps:

– data input;

– data analysis;

– data processing;

– development and choosing of optimal plans;

– monitoring the implementation.

Operational control of the state of PPTS, the timely identification of critical and emergency sections, renovation work are necessary for successful operation ISFR. These works are carried out by repair crews. In this regard, there is the task of calculating their optimal quantity. Since requests for repair work are received at random times, to complete the task of calculating the optimal quantity of repair crews, it is necessary to involve mathematical methods of queuing theory.

Using the database "Background" we can evaluate the intensity of requests for calls to repair crews λ and the average time to eliminate an accident τ. Assume the number of repair crews *n*. Then the process of eliminating emergencies on the pipeline system can be described by a multi-line queuing system. The total flow of requests for maintenance of elevators at the entrance of a specialized organization is formed as a superposition of many flows for maintenance from buildings. Therefore, according to queuing theory [7], it is Poisson (simpler), in which the probability that exactly *k* requests will be receive in a time τ is described by Poisson's formula $P_k(\tau)=\frac{(\lambda\tau)^k}{k!}e^{-\lambda\tau}$, the time distribution between the arrival of neighboring applications is exponential with the distribution function $A(t)=1-\exp(-\lambda t)$. The time distribution of liquidation of pipeline accidents can also be chosen exponential with the distribution function, $B(t)=1-\exp(-\mu t)$, where $\mu=1/\tau$ – intensity of request service. The whole system will be calculated on the hardest mode of operation in an exponential distribution law [8].

So, we received the what's called Markov multilinear queuing system, the study of which was conducted in [9]. If we denote by $\rho=\lambda/\mu$ – then its main characteristics of the developed model are as follows:

- the probability that all crews are free:

$$p_0=\left[\sum_{i=0}^{n-1}\frac{\rho^i}{i!}+\frac{\rho^n}{(n-1)!(n-\rho)}\right]; \qquad (1)$$

- the probability that all crews are busy and there are no queues for service:

$$p_n=\frac{\rho^n}{n!}\cdot\left[\sum_{i=0}^{n-1}\frac{\rho^i}{i!}+\frac{\rho^n}{n(1-\rho/n)(n-1)!}\right]^{-1},\ \frac{\rho}{n}<1. \qquad (2)$$

Average waiting time for the start of service:

$$T_q=\frac{p_n}{\mu n(1-\rho/n)},\ \frac{\rho}{n}<1. \qquad (3)$$

Accordingly, crew load factor (in percent) can be represented as follows:

$$k_z=\left(1-\frac{1}{n}\sum_{i=0}^{n-1}\frac{n-i}{i!}\rho^n\cdot\left[\sum_{i=0}^{n-1}\frac{\rho^i}{i!}+\frac{\rho^n}{n(1-\rho/n)(n-1)!}\right]^{-1}\right)\cdot 100\%.$$

Now, having the basic indicators of system, it is possible to carry out tasks concerning optimum service of requests for a call of repair crews.

From the standpoint of a specialized organization that maintains PPTS, it is necessary to minimize costs, while adhering to certain restrictions, namely: the deviation of the actual time of the beginning of repair from normative should not exceed value T_{kr}. In this case, all requests for the elimination of accidents must be fulfilled. This means that the organization has a certain reserve of capacity to service emergency calls.

It is possible to minimize costs within the developed model only due to the number of crews *n*, aiming at their maximum load. So, we got a task of mathematical programming, which has the form: to find n_m, that maximizes the function k_z, if the conditions of the limitations are fulfilled $T_q<T_{kr}$ and $\lambda/(n\mu)<1$.

We can formulate the task differently: to find n_m, which minimizes the function T_q, if the conditions of the limitations are fulfilled $k_z>k_{min}$ and $\lambda/(n\mu)<1$, where k_{min} – the minimum level of loading of repair crews on PPTS. Both problems can be solved by numerical optimization methods.

Given the low accuracy of approximation of the laws of distribution, the tasks can be solved graphically. Figure 2 shows graphs of the dependence of the start time of the repair request (in hours) depending on the number of repair crews and the load per crew, with a normal repair time of 10 hours.

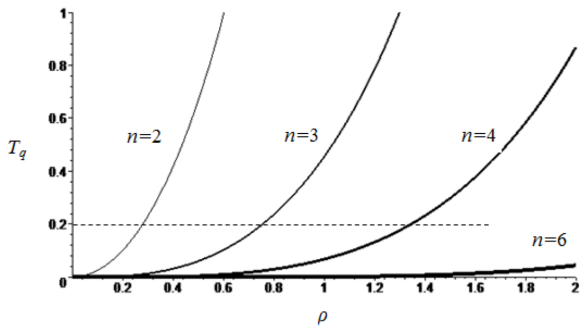

Fig. 2. Charts of delay time of repair starting

By setting the workload per crew and the minimum delay time, you can find the right number of crews. Accordingly, the minimum number of crews is three with a delay time of 0,2 time and a load of 0,8.

Estimated analytical method of emergency repair zones

The development of the system of diagnostics of functional reliability is based on the dividing of the PPTS into emergency repair zones (ERZ) and replacement of the PPTS structure by the macrostructure of ERZ, which completely inherits the functional reliability of the system. For that reason, the analytical method of calculating the functional reliability of the PPTS will be further called the ERZ method. Its main provisions are as follows.

The ERZ method consists of seven successive stages [10]:

1. Formation of a mathematical model of a pipeline network with a complex topological structure in the form of a weighted graph.

2. Dividing the input weighted graph of a complex pipeline network into subgraphs (macroelements), each of which matches to one ERZ.

3. Calculation of the technical reliability of ERZ as an independent macroelement in the functioning of the pipeline network.

4. Conversion of the input weighted graph of a large-dimensional network into a weighted macrograph of a small-dimensional ERZ (replacing the micrograph of each ERZ with one vertex).

5. Construction of a simplified ERZ macrograph relative to an individual consumer of the pipeline network.

6. Construction of a calculation model of the functional reliability of the pipeline network relative to an individual consumer.

7. Formation of a mathematical model of the functional reliability of the network relative to a specific consumer using classical methods of the theory of reliability of technical systems and the direct calculation of functional reliability.

A mathematical model is formed for each consumer $\mathrm{O}_{\text{Сп}k}$ of the pipeline system $k \in \{\overline{1,K}\}$. Here K – a total number of consumers. If several consumers receive the end product from only one ERZ, then the relevant mathematical models of functional reliability coincide.

To form a mathematical model of functional reliability in relation to the consumer $\mathrm{O}_{\text{Сп}k}$ use the following input data:

– calculation model of functional reliability relative to the consumer $\mathrm{O}_{\text{Сп}k}$;

– weight function p on the vertices of the graph ERZ, which determines the technical reliability of each network ARZ;

– weight function p_a on the edges of the graph ERZ, which determines the technical reliability of shut-off valves of the network.

If the calculated model of functional reliability for a random consumer $\mathrm{O}_{\text{Сп}k}$ consists only of series-connected and parallel-connected elements (no bridge connections), then the process of forming a mathematical model corresponds to the algorithm shown in Fig. 3.

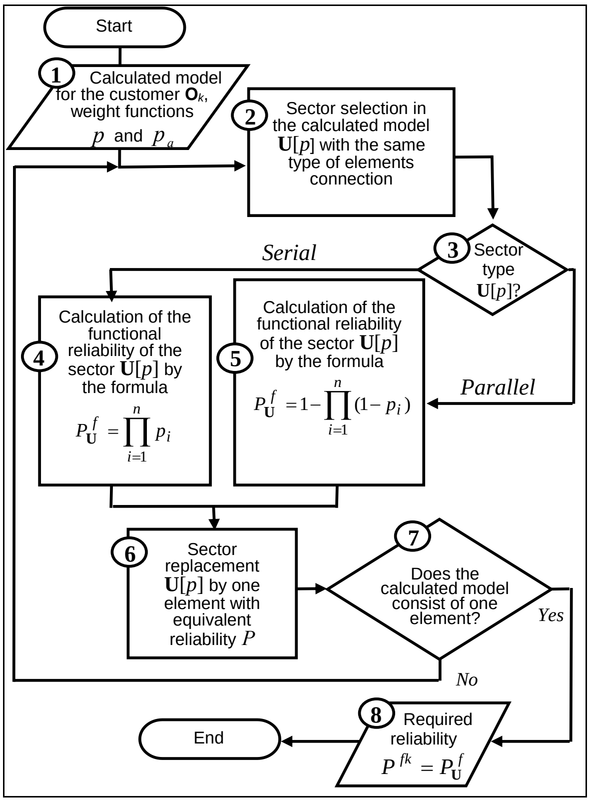

Fig. 2. Scheme of the algorithm for creation a mathematical model of functional reliability of the network regarding to a specific consumer

As follows from the algorithm, the formation of a mathematical model of functional reliability of the network relative to the consumer $\mathrm{O}_{\text{Сп}k}$ is an iterative process of sections replacement $\mathrm{U}[p]$ in the calculation model with the same connection of elements by one element with equivalent reliability.

Equivalent reliability is calculated by the formula $P_{\mathrm{U}}^f = \prod_{i=1}^{n} p_i$ (in the case of series-connected elements) or by the formula $P_{\mathrm{U}}^f = 1-\prod_{i=1}^{n}(1-p_i)$ (in the case of parallel-connected elements). Here n – the number of elements in the same fragment; p_i – the probability of no-failure operation of the element of the pipeline network matching to the i-element of the fragment. The value p_i is selected according to the weight functions p and p_a of ERZ graph.

The iterative replacement process continues until the calculated model consists of only one element. The calculated formula of the reliability P_{U}^f of this element will be the required mathematical model of the functional reliability of the network regarding to the k-consumer of the system [10]:

$$P_k^f = P_{\text{U}}^f, \quad k = \overline{1, K}. \qquad (5)$$

The value P_k^f indicates the probability that the pipeline network provides the end product from the source to the *k*-consumer of the system over a period of time (ordinarilyone year).

The input data in the context of this example are:

– calculated models of functional reliability, which are determined in the previous stages;

– weight function p on the vertices of the ERZ graph;

– weight function p_a on the edges of the ERZ graph.

The algorithm of creation mathematical models under the example gives the following results (generated mathematical models):

– regarding to the first consumer $\text{O}_{\text{Сп}1}$:

$$P_1^f = p_{a1}p_{a2} \times$$
$$\times\left[1-\left(1-p_1 p_{a3} p_3 p_{a5} p_5 p_{a7} p_{a9} p_8 p_{a16} p_{a11} p_{10} p_{a19} p_{a13} p_9 p_{a18} p_{a12} p_7 p_{a15}\right)\times\right.$$
$$\left.\times\left(1-p_2 p_{a4} p_4 p_{a8} p_{a7} p_6 p_{a14}\right)\right] p_{a10}; \qquad (6)$$

– regarding to the second consumer $\text{O}_{\text{Сп}2}$:

$$P_2^f = p_{a1}p_{a2}\left[1-\left(1-p_1 p_{a3} p_3 p_{a5} p_{a6}\right)\times\right.$$
$$\left.\times\left(1-p_2 p_{a4} p_4 p_{a8} p_{a7}\right)\right]; \qquad (7)$$

– regarding to the third consumer $\text{O}_{\text{Сп}3}$:

$$P_3^f = p_{a1}p_{a2}\left[1-\left(1-p_1 p_{a3} p_3 p_{a5} p_{a6} p_5 p_{a17} p_{a11} p_{a10} p_{a19} p_{a9} p_{a8} p_{a16}\right)\times\right.$$
$$\left.\times\left(1-p_2 p_{a4} p_4 p_{a7} p_{a8} p_6 p_{a14} p_{a10} p_7 p_{a15} p_{a12} p_9\right)\right]; \qquad (8)$$

– regarding to the fourth consumer $\text{O}_{\text{Сп}4}$:

$$P_4^f = p_{a1}p_{a2}\left[1-\left(1-p_1 p_{a3} p_3 p_{a6} p_{a5} p_5 p_{a17}\right)\times\right.$$
$$\times\left(1-p_2 p_{a4} p_4 p_{a7} p_{a8} p_6 p_{a14} p_{a10} p_7 p_{a15} p_{a12}\times\right.$$
$$\left.\left.\times\, p_9 p_{a18} p_{a13} p_{10} p_{a19} p_{a11} p_8 p_{a16}\right)\right] p_{a9}; \qquad (9)$$

where $p_{a1}, p_{a2}, ..., p_{a19}$ – weight function value p_a; $p_1, p_2, ..., p_{10}$ – weight function value p.

Calculations of functional reliability by mathematical models (6) – (9) in the example give the following required values $P_1^f = 0{,}9351$; $P_2^f = 0{,}9756$; $P_3^f = 0{,}9232$; $P_4^f = 0{,}9316$.

Conclusions

The obtained mathematical models can be used not only to calculate the value of the indicator of functional reliability, but also to analyze them in order to further improve the design of the network. From the general form of a model, it can be concluded about expediency of new changes in structure of a network. So, the models (6) – (9) show a weak spot in the design of the network related to the valves a_1 and a_2. If the failure of any section does not lead to the cessation of the end product transportation to at least one consumer, the failure of the valve a_1 or a_2 leads to a general cessation of the end product transportation in the network. According to the model (6), if the valve a_{10} fails, the transportation of the end product to the consumer (and only to him) becomes impossible. Similarly, models (8) and (9) indicate that the failure of the valve a_{13} or a_9 leads to the cessation of the end product transportation according to the consumer O_3 or O_4.

Therefore, the analysis of only the type of models (6) – (9) leads to the conclusion that it is necessary to reserve valves a_1 and a_2, as well as the desired redundancy of the valves a_9, a_{10} and a_{13}. In the latter case, to correct the situation it is sufficient to attach to each latch in series another, the same.

The system of the diagnostics of the functional reliability of pipeline systems and the ARZ method in particular bring the greatest benefit to the design of new pipeline systems. This gives an opportunity to make comparisons of alternative structures of the pipeline network by the criterion of functional reliability.

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ІНФОРМАЦІЙНА СИСТЕМА ДІАГНОСТИКИ ФУНКЦІОНАЛЬНОЇ НАДІЙНОСТІ ТРУБОПРОВІДНИХ СИСТЕМ

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Трубопроводи є транспортом, до надійності яких пред'являють підвищені вимоги з точки зору економічних витрат, промислової та екологічної безпеки. Для всіх суб'єктів, пов'язаних з трубопровідною системою, проблема надійності є суперечливою. Усунення суперечності може бути досягнуте тільки за допомогою відшукання компромісного значення поточної надійності, яке в рівній мірі задовольняло б усіх суб'єктів системи. У такій ситуації для успішного вирішення проблеми необхідно мати достовірний метод побудови математичних моделей для розрахунку показників функціональної надійності трубопровідних транспортних систем. Тому актуальною є проблема розробки інформаційної системи діагностики функціональної надійності трубопровідних систем (ІСФН). Виходячи із загальних принципах побудови інформаційних систем, запропонована функціональна схема інформаційної системи аналізу функціональної надійності напірної трубопровідної транспортної системи (НТТС). Основними цілями створення ІСФН є: моніторинг і прогнозування технічного стану трубопроводу в цілому і його елементів; моніторинг ресурсу трубопроводу і резервуарних парків; планування і контроль виконання поточного, середнього та капітального ремонтів. Для успішного функціонування ІСФН необхідний оперативний контроль за станом НТТС, своєчасне виявлення критичних ділянок і аварійних ділянок, проведення профілактичних і ремонтних робіт. Ці роботи виконуються аварійними бригадами. У зв'язку з на базі теорія масового обслуговування розв'язана задача розрахунку їх оптимальної кількості.

У якості базової моделі при розробці ІСФН покладено розбиття ТС на аварійно-ремонтні зони й заміни структури трубопровідної системи (ТС) макроструктурою аварійно-ремонтних зон (АРЗ), яка повністю успадковує функціональну надійність системи. Найбільш важливим етапом метода АРЗ є формування математичної моделі функціональної надійності мережі відносно конкретного споживача за допомогою класичних методів теорії надійності технічних систем і безпосередній розрахунок функціональної надійності. Запропоновано алгоритм побудови математичної моделі функціональної надійності мережі стосовно конкретного споживача і виведені відповідні математичні вирази, які дозволяють розраховувати цю надійність.

Ключові слова: *автоматизована система, діагностика, модель, надійність, трубопровідна система.*