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ASPECTS OF RELIABILITY, EFFICIENCY AND ENERGY SAVING OF GAS PIPELINES AND GAS SUPPLY SYSTEM EQUIPMENT

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ABSTRACT

To ensure the safe operation of gas pipelines of the gas supply system it is necessary to solve the problems of timely detection and elimination of leaks, as well as to determine the volume of natural gas leaks. The most complicated case is the leakage from underground gas pipelines, as gas filtration into the ground, its spreading from the leakage place and accumulation in underground cavities are determined by many factors. Natural gas leaks, in addition to losses, may cause damage to buildings and structures, threat to human health and life due to burning or explosion of the gas-air mixture, financial and economic costs in case of gas shortages, and fines for consumers. Thus, the causes of failures are mainly corrosion wear and local defects of various origins on the walls of gas pipelines, which reduce the capacity of gas pipelines, as well as deteriorate the physical condition of the pipe metal - causing its fatigue under prolonged exposure to operational loads. The listed causes of failures, except for the last one, are well studied. The methods of local defects detection are developed, which will contribute to the improvement of the process of operation and repair and restoration technologies of gas pipelines. In contrast to the existing approaches, the approach presented in the article assumes improvement of the process of operation and repair and restoration technologies of gas distribution networks on the basis of local defects detection methods developed by the authors and improvement of their reliability taking into account the data on the actual technical condition and characteristics of each group of reliability indicators of elements of gas distribution networks.

KEYWORDS

Gas Pipelines, Reliability, Energy Saving, Gas Supply

CITATION

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To ensure the safe operation of gas pipelines of the gas supply system, it is necessary to solve the problems of timely detection and elimination of leaks, as well as to determine the volume of natural gas leaks [1].

The most complicated case is the leakage from underground gas pipelines, as gas filtration in the ground, its spreading from the leakage place and accumulation in underground voids are determined by many factors [1].

Damages of underground gas pipelines occur due to the following reasons: mechanical impacts during excavation works as a result of violation of safety rules and work procedures; corrosion rupture of pipe metal during construction and/or as a result of insufficient control over technical conditions; expansion and opening of gas pipeline joints due to poorly performed construction and installation works [2].

In addition to losses, natural gas leaks can cause damage to buildings and structures, threat to human health and life due to combustion or explosion of the gas-air mixture, financial and economic costs in case of gas shortages and fines for consumers [3,4].

There are two types of pipeline leak detection methods: continuous and periodic monitoring methods.

Based on theoretical studies [4,5], it was found that the process of formation of gas degassing area is divided into two unsteady phases. The first phase starts from the moment of leakage and ends when the gas reaches the soil surface. The second phase of unsteady filtration starts from the moment the gas reaches the soil surface and ends with the transition to the stationary process of gas leakage from the soil to the atmosphere (Fig. 1).

According to the energy balance of Georgia for 2022 [5], the share of natural gas in the total energy consumption was 39 %. At the same time, there is a noticeable decrease in the share of coal, biofuels and waste, one of the reasons for which may be active gasification and replacement of solid fuels with natural gas (Fig. 2). In 2022 Georgia received natural gas from 4 main sources. According to Fig. 2, it is possible to estimate the volume of Georgia's natural gas market and the movement of major gas flows as of 2022 [5].

The natural gas transmission system consists of natural gas pipelines and their equipment that operate or are designed at pressures greater than 1.2 MPa and through which natural gas is transported by a natural gas transmission licencee. Georgian Gas Transmission Company LLC. The transport system currently has 5 receipt points, one of which is a receipt point from local production. Information on each point is provided in Fig. 4.

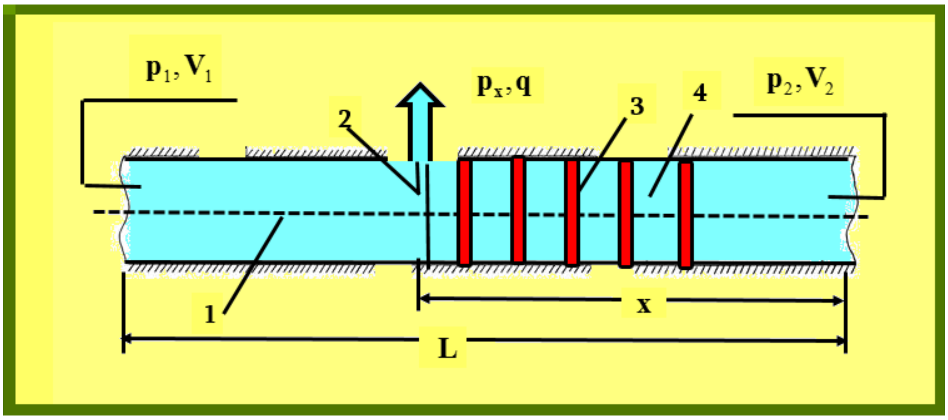

Fig. 1. Leakage from the gas pipeline: 1. gas pipeline; 2. rubber cuff; 3. spacer; 4. protection; $\mathbf{p}_1, \mathbf{p}_2$ *- gas pressure at the initial and final sections of the gas pipeline;* $\mathbf{p}_x$ *- pressure in the leakage zone;* $\mathbf{q}$ *- leakage flow rate;* $\mathbf{V}_1, \mathbf{V}_2$ *- gas volume flow rate at the initial and final sections of the gas pipeline;* $\mathbf{x}$ *- distance to the leakage point;* $\mathbf{L}$ *- total length of the gas pipeline*

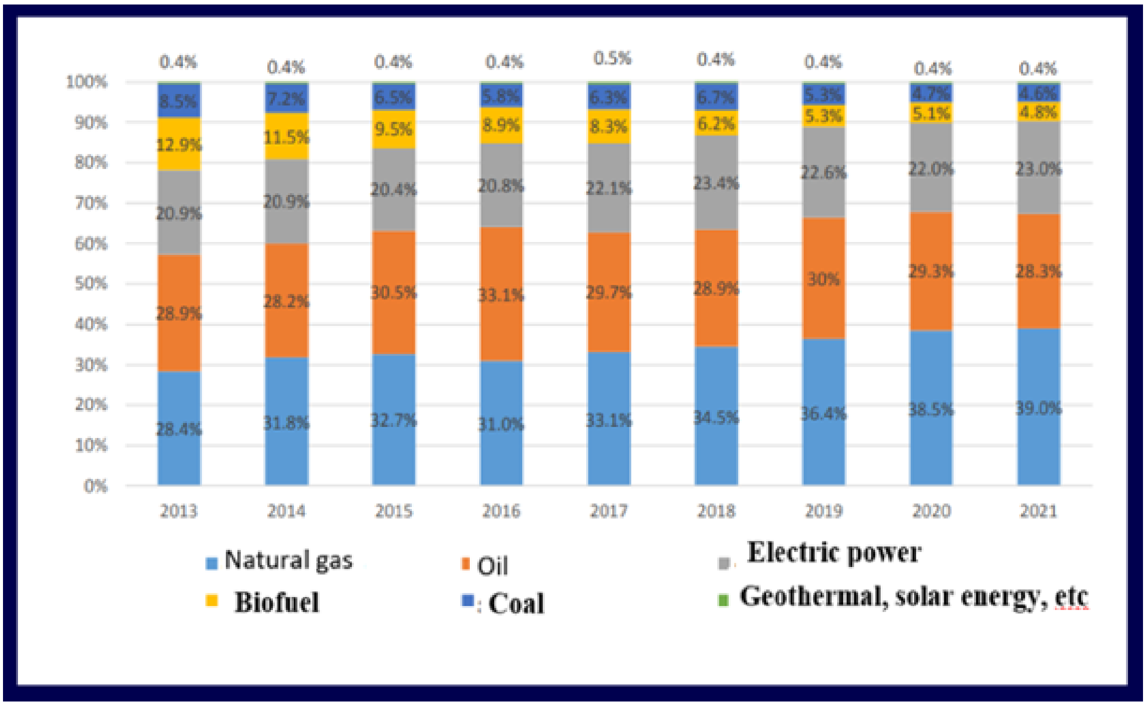

Fig.2 Energy balance of Georgia

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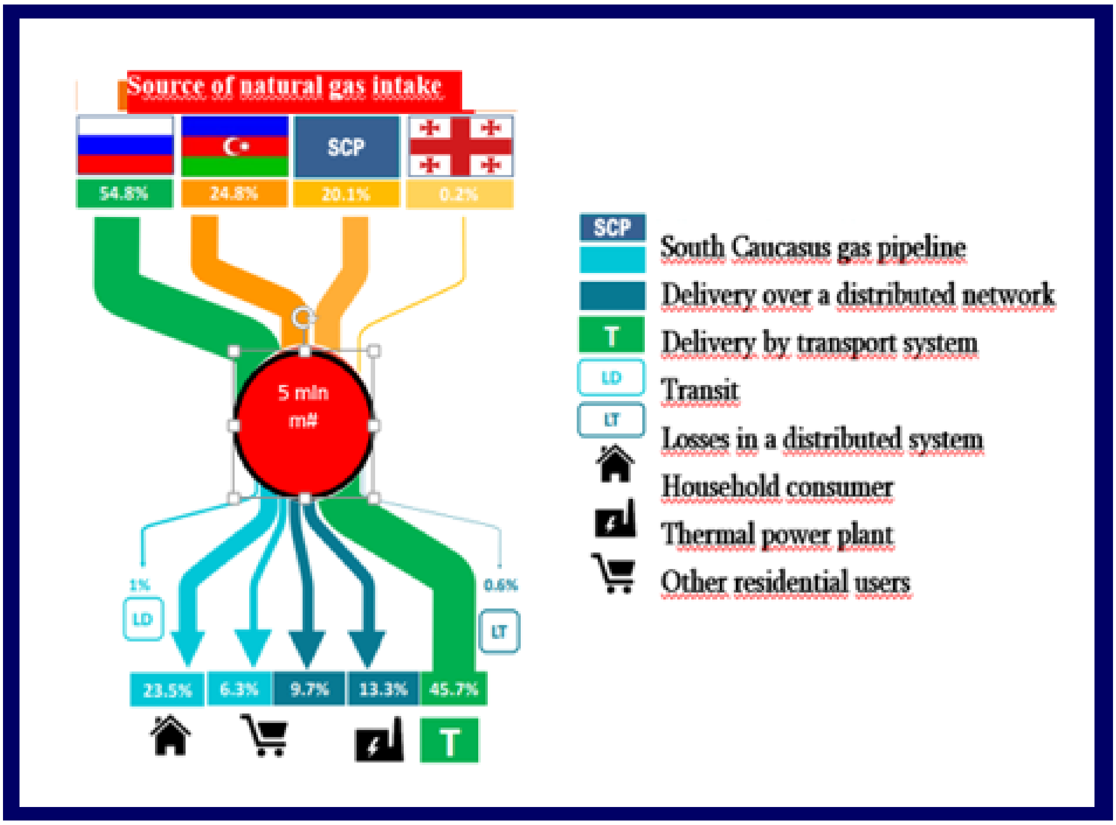

Fig. 3. Natural gas balance

Most accidents occur on the linear part of natural gas pipelines. In addition to the formation of plugs on the pipeline, hydrate formation, freezing of water plugs, etc. occur. Leakage is possible. The location of damage to the linear part of the pipeline can be determined using the "three-point" method: a pressure squared curve is constructed from pressure measurements, and the point where the curve breaks indicates a gas leak or pipeline damage.

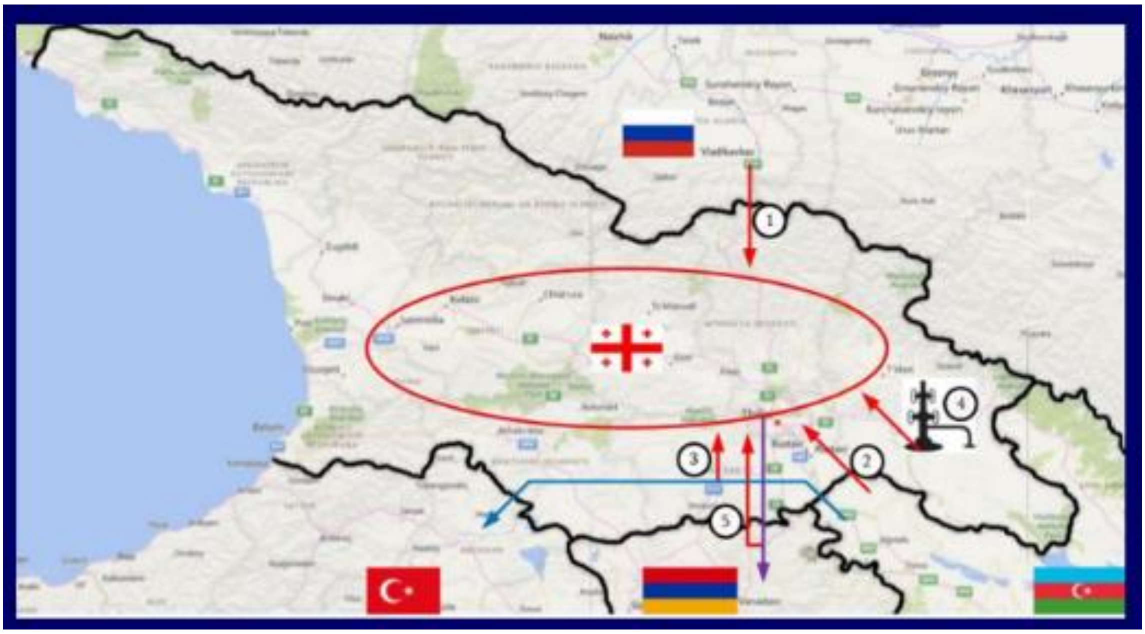

Fig.4. Natural gas receiving points in Georgia: 1. The capacity of the gas pipeline coming from Russia ("Mozdok-Saguramo") is 20 million m3/day. 2. The capacity of the inbound gas pipeline from Azerbaijan ("Kazakh-Saguramo") is 10 million m3/day; 3. The design capacity of the inbound transit gas pipeline from Azerbaijan ("South Caucasus Pipeline") is 64 million m3/day. m3/day, however Georgia has one connection point to the transport system through which 5.5 million m3 of gas can be received per day; 4. The receipt of natural gas from the local extraction point depends on the average daily production of natural gas; 5. The total capacity of the main reverse gas pipeline in Armenia is 3.14 million m3/day

Natural gas consumption by different sectors of the economy is characterised by pronounced seasonality, as is natural gas consumption by household consumers. Figure 5 shows natural gas consumption by household consumers (population) by month [6,7].

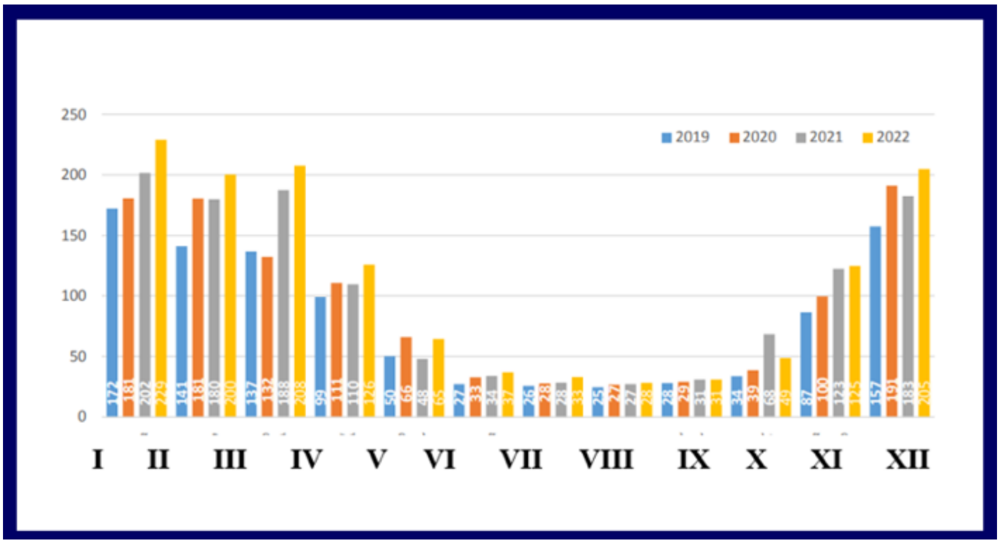

Fig. 5 Natural gas consumption by household consumers (population) by month

However, this method can only detect large gas pipeline damages. The accuracy of the "three-point" method is low and is determined by the accuracy of the graph (Fig. 6) [8].

In theoretical studies the problem is solved using the integral transformation filter [9,10].

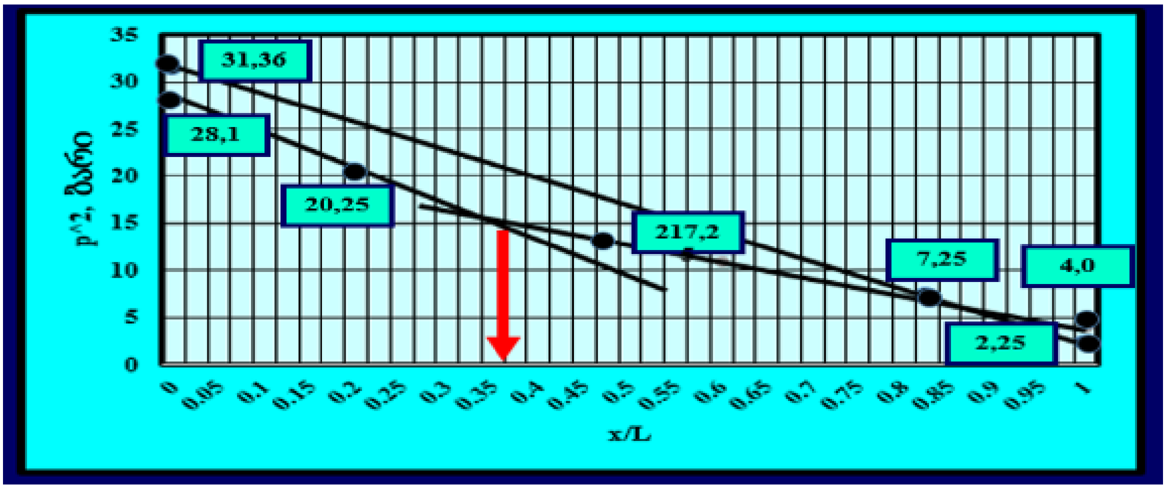

Fig. 6. Determination of pipeline damage using the "three-point" method (example)

$$\omega = \frac{q}{2\pi F}\int_0^\infty \frac{\sin \lambda y_g \sin \lambda y}{\lambda}\left\{\begin{array}{l}[y(x-x_g)-1]\cdot\left[\begin{array}{l}e^{-\lambda(x_g-x)}erfc\left(\frac{x_g-x}{2\sqrt{\varepsilon t}}-\lambda\sqrt{\varepsilon t}\right)- \\ -e^{-\lambda(x_g-x)}erfc\left(\frac{x_g-x}{2\sqrt{\varepsilon t}}-\lambda\sqrt{\varepsilon t}\right)\end{array}\right]- \\ -\sigma(x-x_g)\left[\begin{array}{l}e^{\lambda(x_g-x)}erfc\left(\frac{x_g-x}{2\sqrt{\varepsilon t}}-\lambda\sqrt{\varepsilon t}\right)- \\ -e^{-\lambda(x_g-x)}erfc\left(\frac{x_g-x}{2\sqrt{\varepsilon t}}+\lambda\sqrt{\varepsilon t}\right)\end{array}\right]\end{array}\right\}d\lambda \cdot (1),$$

where $\sigma(x-x_g)$ is a stepwise Heaviside function.

Let's consider leak location. This procedure has been implemented using the "pipeline-leakage" model. In the case of leakage in the pipeline, the leakage cross-section is considered as a boundary cross-section for which the boundary condition is written. Using the steady state model, the leakage location in the pipeline can be determined from the following equation [11]:

$$\mathbf{L_r} = \frac{(\mathbf{p_H} - \mathbf{p_E} - \rho g \Delta \mathbf{h}) - \mathbf{k}\lambda_E \rho \mathbf{L} \mathbf{Q}_E^2}{\mathbf{k}\rho(\lambda_H \mathbf{Q}_H^2 - \lambda_E \mathbf{Q}_E^2)} \quad (2)$$

where, $\mathbf{Q_H}$ - is the gas flow rate measured at the gas pipeline inlet;

λ_H - is the volume of gas consumption calculated from the data available at the inlet to the pipeline;

λ_E - is the pipe resistance coefficient, which is calculated from the data available at the pipeline inlet;

It should be noted that the leakage location value, which is calculated by equation (2), is characterised by large fluctuations (fluctuations).

The numerator and denominator of equation (2) are defined as follows:

$$\mathbf{L_y} = (\mathbf{p_H} - \mathbf{p_E} - \rho g \Delta \mathbf{h}) - \mathbf{k}\lambda_E \rho \mathbf{L} \mathbf{Q}_E^2; \quad (3)$$

$$\mathbf{L_x} = \mathbf{k}\rho(\lambda_H \mathbf{Q}_H^2 - \lambda_E \mathbf{Q}_E^2); \quad (4)$$

Then, $$\mathbf{L}_{\mathbf{y}} = \mathbf{L}_{\mathbf{r}} \times \mathbf{L}_{\mathbf{x}}. \quad (5)$$

When the target function $\sum_{i=1}^{n}\left(\mathbf{L}_{yi} - \mathbf{L}_{r} \times \mathbf{L}_{xi}\right)^{2}$ reaches a minimum, the leakage location is determined by the relationship:

$$\mathbf{L}_{r} = \frac{\sum_{i=1}^{n}\left(\mathbf{L}_{yi} \times \mathbf{L}_{xi}\right)}{\sum_{i=1}^{n}\mathbf{L}_{xi}^{2}}. \quad (6)$$

Random failures are the result of gradual qualitative changes that are not controlled under operating conditions (rupture caused by metal fatigue, depressurisation of pipelines). Any engineering and technical system is an object of recovery, and the parameter of failure flow serves as an indicator of its reliability:

$$\omega(t) = \lim_{\Delta t \to 0} \frac{M[r(t+\Delta t)] - M[r(t)]}{\Delta t}, \quad (7)$$

where, M - mathematical expectation of failures;
r(t) - number of failures at time t;
r(t+Δt) - number at time (t+Δt);
ω(t)- average number of failures in a short period of time;
n(t)- the ratio of the average number of expected failures of a working device in the time interval to the number of all devices per unit of time, provided that all devices are replaced by serviceable devices after repair.

$$\omega(t) = n(t)/(N(\Delta t)\cdot\Delta t), \quad (8)$$

where,
$\mathbf{N}(\Delta \mathbf{t})$ - is some number of full-scale samples, and the testing process in the time interval Δt remains constant, since all devices having failures must be replaced or repaired. In general, it is a function of time $\omega(t)$ (Fig. 7). The value of ω is influenced by: factors of fatigue and wear of elements, as well as scheduled repairs.

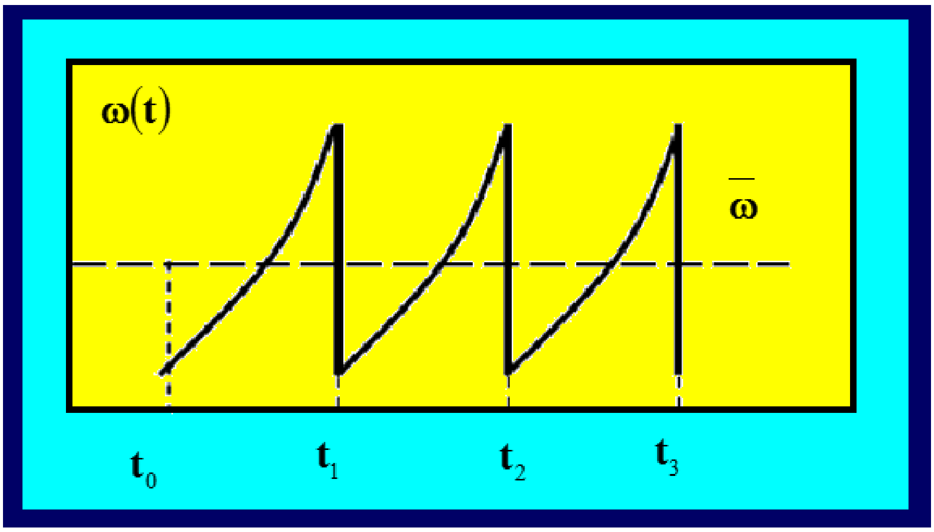

Fig. 7. Operation flow: t_1 , t_2 , t_3 time of overhaul; t_0- time of end of operation

From the analysis of the causes of failure of the device of engineering systems, it can be expressed as a sum [10,11]:

$$\omega(t) = \omega_1(t) + \omega_2 \tag{9}$$

Where, ω(t)- depends on device wear, fatigue and service life;

ω_2 - is not a function of time. It is due to the external impact on the utility network.

Failure flow is caused by fatigue of protective coating, corrosion of metal parts.

Failure flow $\omega_1(t)$can be caused by fatigue of protective coating, corrosion of metal parts, wear of bearings and friction joints, physical and chemical factors of changes in lubricant properties, fatigue and insulation breakdown, etc...,

Climatic loads, installation defects, damage to pipelines and their insulation, lightning, fire, etc. are determined by the component ω_2. The value ω_2 =const - does not depend on long-term operation, overhaul, i.e. is determined by random causes.

As can be seen, the causes of failures are mainly corrosion wear and local defects of various origins on the walls of gas pipelines, which reduce the throughput capacity of gas pipelines, as well as increase fatigue of pipe metal (deterioration of physical condition) under prolonged exposure to operational loads. The listed causes of failures, except for the last one, are well studied.

In the practice of operation of equipment of engineering systems, when determining the operating time for normative failures $\overline{\omega}$, it is assumed that it does not depend on the service life of the engineering system, from which the calculation of the frequency of overhaul begins. An important indicator of reliability of the device operation in the inter-repair period is the failure rate of the product $\lambda(t)$ (Fig. 8).

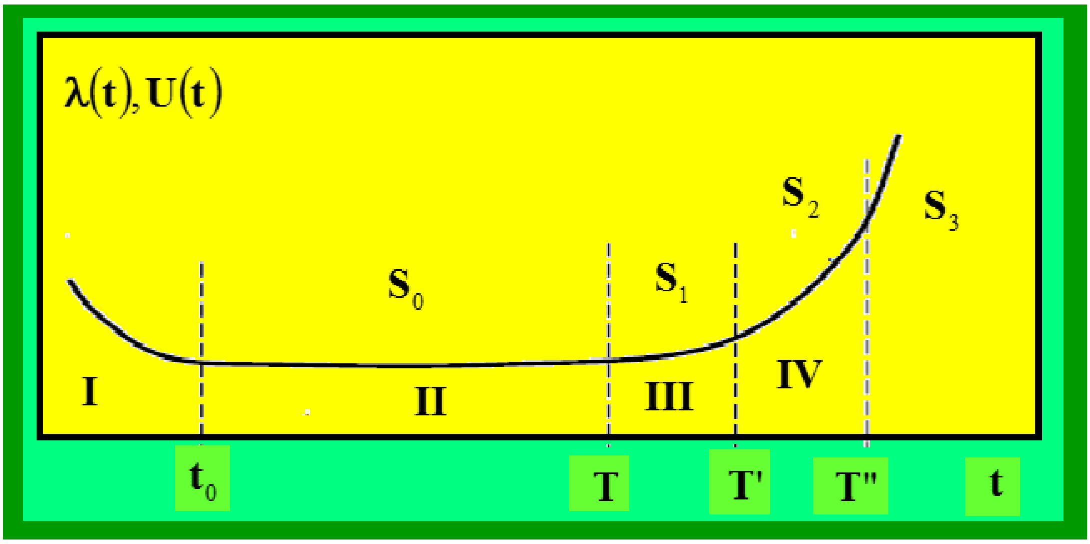

Fig. 8. Change of reliability (state) of the device depending on the time of operation in the period between overhauls: I-stage of working out of details of a particular unit; - II-stage of normal operation; III-stage of fault or wear formation; IV-stage of abnormal development of fault or wear; S_0- normal state; S_1- permissible state; S_2- dangerous state; S_3- accident

$\lambda(t)$ there is a conditional probability of product failure in the interval $(t + \Delta t)$, where - t time of gas pipeline operation before failure, i.e:

$$\lambda(t) = f(t)/P(t) = a(t)/P(t). \tag{10}$$

Here $a(t)$- failure rate of the device (product) - is the ratio of the number of failed samples per unit of time to the initial number of samples during monitoring, provided that the failed samples are not repaired or replaced with serviceable ones.

In practice, a representation in the following form is used to determine the results of technical falsehood statistics [11]:

$$a^*(\Delta t) = n(\Delta t)/(N_0 \cdot \Delta t) \,, \qquad (11)$$

where, $n(\Delta t)$ - the number of failures in the time interval:

Δt - the value of the time interval into which the object observation period is divided into equal segments.

Fig. 8 shows the dependence characteristic of a mechanical device. It allows us to interpret the diagnostic state parameter S as it changes in time and compare it with the threshold values of the measured signals. Suppose that the change in the technical state $\Phi_{\mathbf{Nor}} = 1$, depending on the measured signal,can be qualitatively represented in the form of some decreasing function (Fig. 9).

Having constructed the boundary values of the measured signals U according to the obtained classes of possible states S_0-S_2, as well as taking into account the selected model $\{\mathbf{S}_1(\mathbf{d_{ij}}), \mathbf{S}_2(\mathbf{d_{ij}}), ..., \mathbf{S_k}(\mathbf{d_{ij}})\}$ of the obtained quantitative estimates of the technical state $\Phi\{\mathbf{S}_1(\mathbf{d_{ij}}), \mathbf{S}_2(\mathbf{d_{ij}}), ..., \mathbf{S_k}(\mathbf{d_{ij}})\} = \Phi(\mathbf{U})$, it is possible to obtain the corresponding boundary values and technical estimates of the selected essential properties of the product and the image itself. The structure of the technical state estimation process for acceptable possible classes of states and their boundaries is shown in a general form in Fig. 9.

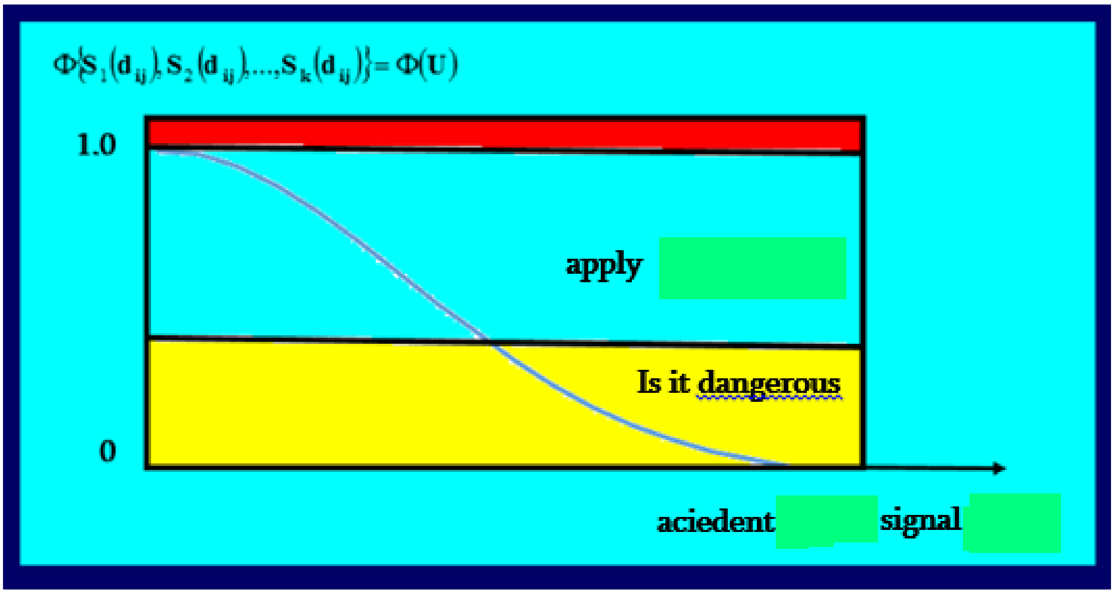

Fig. 9. Change of the technical state according to the values of the measured signals

Thus, in contrast to existing approaches, the approach we propose suggests improving the repair maintenance of the gas distribution network on the basis of the developed methods of local defect detection and improving their reliability, taking into account the data on the actual technical condition and characteristics of each group of reliability indicators of the gas distribution network elements. The procedure of technical condition assessment in accordance with the established boundaries of classes according to the essential properties of the object of diagnostics is presented in Fig. 10.It should be noted that, unlike the existing approaches, the methods of local defect detection have been developed, which will contribute to improving the process of gas pipelines operation and technologies of their repair and restoration.

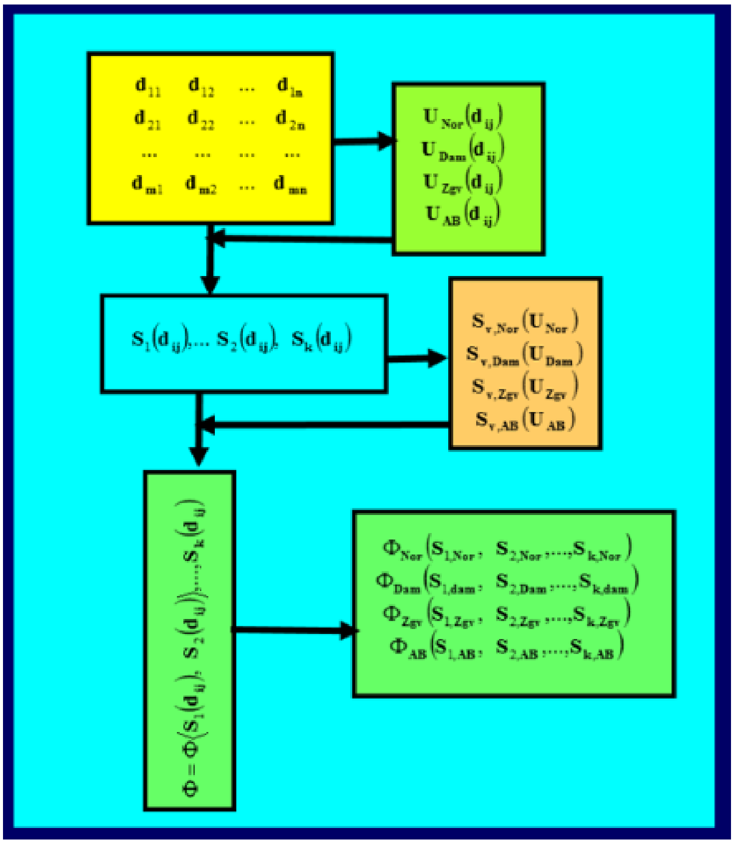

Fig. 10. Procedure of technical condition assessment in accordance with the established class boundaries in relation to the essential properties of the diagnostic object

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