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Formalization of the design model of gas-main pipelines infrastructure failure

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Abstract
Based on the analysis of mathematical models of the pipelines failure process under conditions of incomplete information, a conceptually new approach in the framework of the adopted strategy was chosen to implement the optimal scheduling of the control and rehabilitation measures mode for the most efficient use of material and equipment and to ensure the reliable operation of the gas pipeline system. The result is a mathematical model that adequately describes the actual process of maintenance of the gas-main pipelines infrastructure and allows to solve the task complex for its improvement.

Strategy as the main characteristic of the operation process of the maintenance and repair (MR) system of gas-main pipelines (GMP), establishes the type, volume and frequency of the implementation of measures on the maintenance and repair of infrastructure.

The main purpose of the maintenance and repair system of GMP infrastructure, consisting of linear repair and maintenance departments and services is the implementation of control and rehabilitation measures (CRM). CRM are focused on more narrow tasks than during the whole set of works on MR. At the same time control and rehabilitation measures are the main factor for the maintainability engineering of the existing gas pipeline systems. It is about the control measures of the infrastructure condition and tightness, the early recognition of damages and their prompt repair.

For the successful and effective implementation of CRM on the existing gas pipeline systems to ensure reliable and uninterrupted gas supply to the consumer three conditions are required:

- effective means of the MR tightness (state) control;
- the existing reclamation units on infrastructure maintenance;
- rational program (strategy) of CRM.

However, in the framework of the strategy the optimal planning of the CRM mode should be implemented for the most efficient use of material and technical resources and to ensure reliable operation of the gas pipeline system.

In fact, the task of CRM strategic planning is a typical example of an extremal problem, which optimal solution corresponds to the maximum or minimum value of some objective function.

Solution of such problems includes the following main phases:

- formalization of the gas pipeline failure process model;
- formation of the design model (strategy) of control and rehabilitation measures;
- selection of the CRM performance indicators within the adopted strategy;
- development of the mathematical model for assessment of the CRM efficiency;
- synthesis of optimal solutions for different values of the initial data and boundary conditions.

Despite these difficulties in assessing the infrastructure reliability level, the CRM planning should take into account the actual performance reliability and maintainability values of the system serviced.

It is not always possible to obtain all the necessary information to assess the reliability values in practice. In this case, it is necessary to use mathematical methods of making decisions under conditions of incomplete information about the state of the object of study.

In such a case, it is advisable to introduce the process of emergence and development of infrastructure failures as a two-stage model of transitions and states of the system (Figure 1). According to the accepted model, each element of the system can be in three states:

- operative (normal operation)
- invalid, but operational (damage existance)
- inoperable (failure)

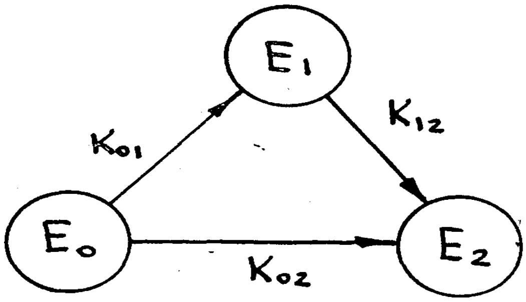

Figure 1. Directed graph of the gas-main pipeline infrastructure state

As part of the two-stage model of the gas pipeline failure during operation it is advisable to distinguish the following types of damages (states):

- failure (accident), big damage, makes a shut down of pumping or gas or poses a risk as a source of fires, explosions, etc.;
- damage (failure), does not violate the process of gas pumping, pre-emergency condition that poses a threat of of the gas pipeline failure;
- minor damage is not dangerous and does not require immediate actions.

Formalize the design model of the gas-main pipeline infrastructure failure within the proposed two-stage model.

Analysis of the researches in this area [1,2] allows to accept the assumption that the process of the gas pipeline "aging" and failure is a random process of emergence and development of time homogeneous damages. Moreover, the process of defects occurrence is described by a simple Poisson stream of random events, that is characterized by the intensity λ. The damage size q is an independent random variable with the density of probability $U_{ут}(q)$.

The appeared damage has the ability to self-demonstration in some time, is considered as an independent random variable with distribution function F(t). The gas pipeline gap (accident) will be taken as the damage self-demonstration.

Analysis of damage self-demonstration allows to take an exponential distribution function:

$$F(t) = 1 - \exp\left(-t/\tau_{av}\right) \quad (1)$$

where τ_{av} - the average lifetime of damage since its occurrence until the self-demonstration.

The adoption of exponential distribution law of the MR infrastructure reliability indices is a significant assumption, reflected in the pattern of the gas pipeline failure.

Distribution law, of course, can be defined in two ways. Firstly, statistically, having tested the hypothesis about the distribution function belonging to a particular parametric class. And, finally, physically, on the basis of a mathematical research of the system failure physical model. The disadvantage of the first method is that a certain type of distribution for a certain period of time is not not necessarily reserved outside this interval (insufficient value), the second method requires the study of the physical processes occurring with the system elements, to evaluate which today is almost impossible (inability to assess).

The exponential distribution is the most commonly used in problems of complex systems reliability for the following reasons:

- significant simplification of the calculations and the opportunity to present the basic expressions analytically;
- sufficient approximation to the real distribution function of reliability indices;
- possibility to use minimum statistical information;

Furthermore, the use of an exponent distribution in the description of reliability functions of systems, similar to the GMP infrastructure is demonstrated in many papers [2,3,4], that allows to take it as the basis for the achievement of operational reliability of gas-main pipelines.

The statistics analysis of failures and diseases on infrastructure also shows that the intensity of operational accidents changes slowly and is practically the constant, which depends on the operating conditions and other external influences.

This confirms the possibility to consider the appearance of the infrastructure damages and failures as the easiest stream of random events.

The operation and maintenance specifics of individual elements [4] of the GMP infrastructure gives rise to consider the failure process of these objects of system. When planning control and rehabilitation measures under the elements (pointed objects) of infrastructure, only those objects should be pointed out, the control and maintenance of which require additional operations (as opposed to the operation of actual pipe). These include:

- line valve station;
- hotwells;
- aerial crossings through the rivers, ravines;
- undercrossings beneath roads and railways.

Their operation includes conducting the complex of control and adjustment and maintenance works requiring certain costs. And there may be so-called functional failures, which are determined by the impossibility of an object to perform its production purposes. Often these faults are hidden, that is appear only at a certain point, or identified with a special control. The damages and failures associated with the gas pipelines depressurization are related to larger damages, which require immediate actions to restore the object. They are characterized by a certain specific damage q, which depends on the parameters of damage. In the case of undetected functional failure q = 0 is taken. In this connection, it is considered that undetected failures are not detected independently. Nonfailure operation time is an independent random variable with distribution function F(t).

One of the most important issues to improve the MR system of the GMP infrastructure is to choose the rational operation strategy for the purpose of further planning of optimal control and rehabilitation measures.

In forming the maintenance and repair strategy it is necessary to consider the specifics of the real infrastructure operation, as well as the requirements of the regulations, which impose severe restrictions on the possible options for design models of MR.

A two-stage model of the gas-pipeline failure is taken as the basis for the calculation scheme of CRM. The strategy in this case is formed, depending on the control type, state of objects, nature of repair and maintenance measures and operating principles of the impact on system on the control results. The GMP infrastructure (object) of control and reclamation maintenance can be in a finite of number of states. $E = \{E_1, E_2, ...E_n\}$. A random process of the system states evolution in time is described by the function X(t) with graduated trajectories. The analysis of the operating practice of the GMP infrastructure, the requirements of the industry regulations allow to formulate the following possible states of the system:

$$X(t)=\begin{cases} E_1 - \text{ operative condition} \\ E_2 - \text{ invalid, but operational condition} \\ E_3 - \text{ inoperable (failure)} \\ E_4 - \text{ repair and maintenance measures} \\ E_5 - \text{ control} \end{cases}$$

Design model of control and rehabilitation measures (CRM strategy) is formulated as follows:

- periodic inspections of state (tightness) of the infrastructure (with a period δ) are strictly carried out on GMP;

- in case of failures and damages (blue holes, leakings and similar states) emergency reclamation works are carried out;

- in the case of failures (self-demonstration of damage) in the interrevision period emergency response and restoration operations are held.

State transition graph of the system during the CRM is shown in Figure 2.

It should be assumed that the infrastructure failures are disclosed almost instantly and absolutely definitely. Control probability is characterized by the total probability of damage detection P based on the inspection results. It should be accepted the assumption that the MR measures are implemented almost instantly (in disproportionately less time on δ and 1/λ) and do not affect the level of gas pipeline reliability indices.

The purpose of the rational planning of the GMP infrastructure maintenance and repair measures is to minimize the objective function of the total unit costs, taking into account all its components with the chosen strategy of CRM:

$$F\left(3_\Sigma^{CRM}\right) \Rightarrow \min \qquad (2)$$

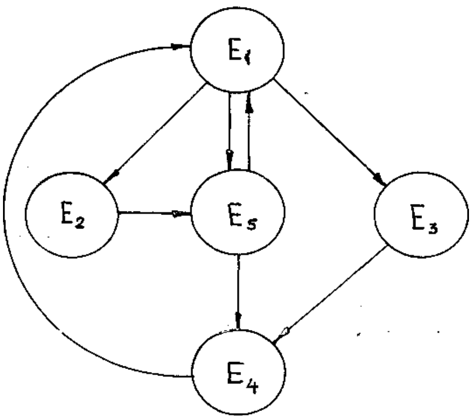

Figure 2. The state transition graph of the gas-main pipelines infrastructure in the CRM (E_1- operative condition; E_2 - invalid operational condition; E_3 - inoperable (failure); E_4 - restoration; E_5 - control)

This task is quite traditional [3,5]. To solve it, it is necessary to get the integral expressions of the objective and performance function, its components, as well as to find the optimal values of the function at different initial data and boundary conditions. The main formalization principles of the proposed mathematical model of CRM is a probabilistic approach and accounting of the reliability factor of the GMP infrastructure.

The proposed CRM design model is estimated by the following integral indicator:

$$\overline{3}_\Sigma^{CMR} = 3_f \cdot \bar{n}_f + 3_T \cdot \bar{n}_n + 3_{pr} \cdot \delta^{-1} + \bar{Q} \qquad (3)$$

where $\bar{n}_f$, $\bar{n}_n$ - composite index that assess accordingly the average specific intensity of accident failures and damages control on the operated area, [1/day]; $\bar{Q}$ - composite index assessing the specific damage caused by gas losses [UAH./day];

3_f, 3_n - maintainability indicators of infrastructure, that estimate the average costs per one failure, damage.

Given the above calculation models of the infrastructure destruction and maintenance take the intensity of the flow of failures and damages λ as constant, in the case of a one-parameter exponential distribution to characterize the reliability of the system restrict oneself by a single indicator λ [1/day].

The process of damage developing to its self-demonstration (failure) is described by a random lifetime of fault with the distribution function F(t).

Among the indicators of maintainability (except 3_f, 3n) and service efficiency of the gas pipeline system it should be taken into account:

- the costs of control measures (periodic patrolling) - 3_{pr} [USD.];

- damage from the gas loss at drilling during the repair C [USD];

- average specific value of the damage caused by a single fault - q [USD/day];

- the probability of damages detection based on the inspection results - P;

- control periodicity- δ [days].

Consider the steady-state mode of unlimited length service with periodic status monitoring of infrastructure at 1/δ and allowed ability P.

The specific number of damages detected on the results of inspections and did not appear on their own, is:

$$\overline{\Pi}_{\Pi} = \frac{1}{\delta}\left[\lambda\int_0^{\delta} P\overline{\Phi}(t)dt + \lambda\int_{\delta}^{\delta} P(1-P)\Phi(t)dt + \lambda\int_{2\delta}^{3\delta} P(1-P)^2\Phi(t)dt + \ldots\right] =$$

$$= \frac{1}{\delta}\lambda P\sum_{K=0}^{\infty}(1-P)^K\int_{K\delta}^{(K+1)\delta}\overline{\Phi}(t)dt$$

(4)

where $\overline{\Phi}(t) = 1 - \Phi(t)$ - the non-transition probability of damages caused at failure of the time t (the reliability function).

System failures are the result of self-demonstration of damage (fault), which were formed in the period between two verification inspections or undetected during the previous inspection tests.

The specific number of failures (accidents) is defined as follows:

$$\overline{\Pi}_{ab} = \frac{1}{\delta}\left[\lambda\int_0^{\delta}\Phi(t)dt + \lambda\int_{\delta}^{2\delta}(1-P)\left[\overline{\Phi}(t-\delta) - \overline{\Phi}(t)\right]dt + \right.$$

$$\left. + \lambda\int_{2\delta}^{3\delta}(1-P)^2\left[\overline{\Phi}(t-\delta) - \overline{\Phi}(t)\right]dt + \ldots\right] =$$

$$= \frac{1}{\delta}\lambda\int_0^{\delta}\Phi(t)dt + \frac{1}{\delta}\lambda\sum_{K=1}^{\infty}(1-P)^K\int_{K\delta}^{(K+1)\delta}\left[\overline{\Phi}(t-\delta) - \overline{\Phi}(t)\right]dt$$

(5)

It is advisable to assess the overall index of specific damages from gas losses into the atmosphere in two stages:

$$\overline{Q} = \overline{Q}_{gl} + \overline{Q}_{og} \qquad (6)$$

where $\overline{Q}_{gl}$ - specific damage from the gas loss at faults;

$\overline{Q}_{og}$ - specific damage from outgassing from the area during the restoration works.

It is rather difficult to rate the specific damage caused by the loss of gas from the damage appearance (blowing) to its liquidation (after detection). Equipment capable to fix the blowing volumes through the microswitches and connections is not available. Systems of continuous monitoring of the pipelines integrity are still under experimental and theoretical developments. Statistical methods are unacceptable due to lack of such information. It should be noted that the value of specific gas losses through the switches and sources is of a very wide range. With a certain degree of accuracy, the average specific losses q can be determined based on indirect data, depending on the parameters (mode) of transfer, nature and extent of damage. Then the specific waste of gas losses due to damage with the average daily loss q define:

$$\overline{Q}_{gl} = \frac{1}{\delta}\left[\lambda\int_0^{\delta}dtq\int_0^{\delta-t}\Phi(x)dx + \lambda\int_{\delta}^{2\delta}dtq\int_{t-\delta}^{t}(1-P)\overline{\Phi}(x)dx + \right.$$

$$\left. + \lambda\int_{2\delta}^{3\delta}dtq\int_{t-\delta}^{t}(1-P)\overline{\Phi}(x)dx + \ldots\right] =$$

$$= \frac{1}{\delta}\left[\lambda\int_0^{\delta}dtq\int_0^{\delta-t}\overline{\Phi}(x)dx + \lambda q\sum_{K=1}^{\infty}(1-P)^K\int_{K\delta}^{(K+1)\delta}dt\int_{t-\delta}^{t}\overline{\Phi}(x)dx\right]$$

(7)

As a rule, the largest share in the total volume of gas losses to the atmosphere amounts the losses during outgassing from the gas pipeline. The volume of the bleeded gas is determined by the characteristics of the area (the length of the overlapped area between two pipeline valve, pipeline diameter) and the parameters of the pumped gas (pressure, temperature, compressibility factor). It is not difficult to determine the average value of costs (waste) C of gas losses by bleeding before the hot works on route.

Given this, the specific damage from gas bleed from the areas of gas transportation served system is:

$$\overline{Q}_{og} = \frac{C}{\delta}(1 - P_{no}) \qquad (8)$$

where P_{no} - the total probability of not identifying damages on the results of all inspections during the infrastructure operation.

$$P_{no} = \prod_{K=0}^{\infty}\prod_{t=0}^{\delta}\sum_{r=0}^{\infty}\frac{(\lambda dt)^r}{r!}e^{-\lambda dt}\left[1 - \overline{\Phi}((K+1)\delta - t)(1-P)^K P\right]^r =$$

$$= \prod_{K=0}^{\infty}\prod_{t=0}^{\delta}\exp\left\{-\lambda P(1-P)^K\overline{\Phi}((K+1)\delta - t)dt\right\} =$$

$$= \prod_{K=0}^{\infty}\exp\left\{-\lambda P(1-P)^K\int_0^{\delta}\overline{\Phi}((K+1)\delta - t)dt\right\} =$$

$$= \exp\left\{-\lambda P\sum_{K=0}^{\infty}(1-P)^K\int_{K\delta}^{(K+1)\delta}\overline{\Phi}(x)dx\right\}$$

(9)

Given the (7) - (9), expression (6) has the form:

$$\overline{Q} = \frac{1}{\delta}\left[\lambda\int_0^{\delta}dtq\int_0^{\delta-t}\overline{\Phi}(x)dx + \lambda q\sum_{K=1}^{\infty}(1-P)^K\int_{K\delta}^{(K+1)\delta}dt\int_{t-\delta}^{t}\overline{\Phi}(x)dx + \right.$$

$$\left. + C\left(1 - \exp\left(-\lambda P\sum_{K=0}^{\infty}(1-P)^{K}\int_{K\delta}^{(K+1)\delta}\overline{\Phi}(x)dx\right)\right)\right]$$

(10)

Accepting the above assumption of the exponential nature of the distribution function of the random lifetime damage to the self-demonstration (failure), the average lifetime of damage τ_{av} is defined as the expectation of a random time between failures;

$$\tau_{av.} = M_{\xi} = \int_0^{\infty} t d\Phi(t) = \int_0^{\infty} \overline{\Phi}(t) dt =$$

$$= \int_0^{\infty} e^{-\lambda t} dt = \frac{1}{\alpha} \quad (11)$$

More convenient to write:

$$F(t) = 1 - \exp(-\alpha t) \quad (12)$$

where $\alpha = 1/\tau_{av}$.

Omitting the numerous intermediate transformations, taking into account (11), (12), and obtain an expression of generalized indicators (4), (5) and (10) in its final form:

$$\overline{\Pi}_n = \frac{\lambda P}{\alpha \delta} \cdot \frac{\left(1 - e^{-\alpha \delta}\right)}{1 - (1 - P) e^{-\lambda \delta}}; \quad (13)$$

$$\overline{\Pi}_f = \lambda - \overline{\Pi}_n; \quad (14)$$

$$\overline{Q} = \left(C + \frac{q}{\alpha}\right)\left(\lambda - \overline{\Pi}_n\right) + \frac{C}{\delta}\left[1 - \exp(-\Pi_n \delta)\right] \quad (15)$$

Thus, the objective function of total average unit costs of implementing control and rehabilitation measures within the chosen strategy is:

$$\overline{З}_{\Sigma}^{CMR} = \frac{З_{or} + C}{\delta} + \lambda\left(З_f + \frac{q}{\alpha}\right) - \left(З_f - З_n + \frac{q}{\alpha}\right)\overline{\Pi}_n - \frac{C}{\delta}\exp\left(-\overline{\Pi}_n \delta\right)$$

(16)

where $\overline{\pi}_n$ - is described by expression (13).

The mathematical model evaluating the effectiveness of control and rehabilitation measures in the framework of the adopted MR strategy adequately describes the actual process of the GMP infrastructure maintenance and allows to solve complex problems for its improvement.

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