

EVALUATION OF THE RESIDUAL SERVICE LIFE OF MAIN PIPELINES WITH REGARD FOR THE ACTION OF MEDIA AND DEGRADATION OF MATERIALS

O. Ye. Andreikiv,^{1,2} I. Ya. Dolins'ka,³ I. P. Shtoiko,³
O. K. Raiter,³ and Yu. Ya. Matviiv⁴

UDC: 539.375; 539.4

We proposed new procedures for the evaluation of the residual service life of main pipelines with surface cracks under the action of a long-term constant gas pressure in gas pipelines, a variable pressure in oil pipelines, hydrogenation, and soil corrosion. The degradation of the materials is taken into account. Since the time dependence of the degree of degradation is insignificant, it is analytically described by linear dependences. The energy approach is used to determine the residual service life of the pipes. The corresponding computational models (differential equations with initial and final conditions) are developed. For specific pipe materials (Kh52, Kh60, and Kh70 steels), the residual service life is computed under long-term static and variable loads, in the presence of hydrogenation and soil corrosion with regard for the degradation of the materials for 30 yr.

Keywords: residual service life of main pipelines, hydrogenation, soil corrosion, degradation of materials, Kh52, Kh60, and Kh70 steels.

Introduction

The application of main pipelines proves to be the most cost-efficient method of transportation of oil, gas, and oil products. Pipeline systems can be regarded as the most important part of the power-generating complex whose trouble-free functioning is of exceptional importance for the state. Thus, the main task is to guarantee their reliability. However, the solution of this problem is complicated by the fact that the service life of more than 37% of all main pipelines exceeded the term of amortization of the linear parts (33 yr) and 38% of pipelines are in service for 20–33 yr. In general, the system of main pipelines with so "solid age" entered the third period of their life cycle, i.e., the period of total degradation of the metal and frequent failures. Therefore, in analyzing the residual service life of pipelines, it is necessary to take into account the degradation of their materials, i.e., the changes in their mechanical, fatigue, and strength characteristics in the course of operation.

At present, the problem of degradation of the materials of pipelines operating for 30–60 yr is extensively investigated and the variations of their mechanical characteristics are analyzed (see, e.g., [1, 2]). However, in order to determine the residual service life of pipelines with regard for the operating conditions, it is necessary to know various important characteristics of materials of the pipes, such as the static and cyclic crack resistance of the materials, their behavior as functions of time, and the influence of soil corrosion and hydrogenation on these characteristics.

¹ I. Franko Lviv National University, Lviv, Ukraine.

² Corresponding author; e-mail: andreykiv@ipm.lviv.ua.

³ Karpenko Physicomechanical Institute, Ukrainian National Academy of Sciences, Lviv, Ukraine.

⁴ Lutsk National Technical University, Lviv, Ukraine.

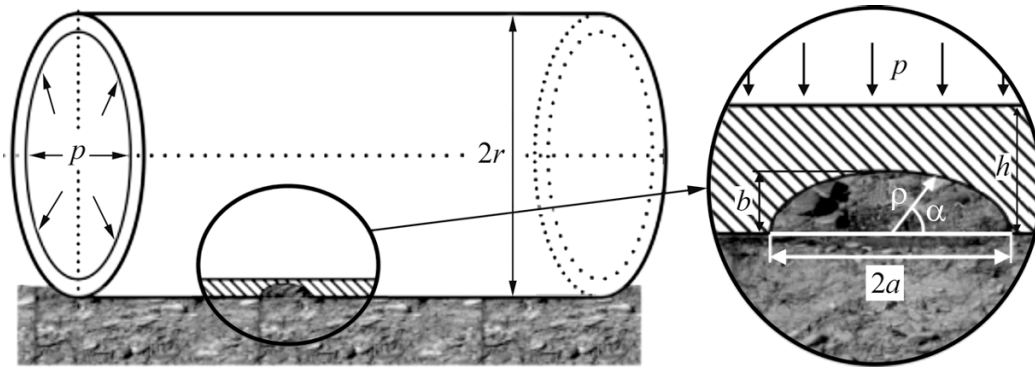


Fig. 1. Loading mode of the pipe weakened by a crack and its contact with the ambient medium.

The amount of available experimental results of this kind is insufficient, which creates difficulties in the development of the corresponding methods aimed at the evaluation of the residual service life of pipelines.

In what follows, we propose new methods for the evaluation of the residual service life of pipelines. These methods take into account the results accumulated earlier [3–6] in modeling the process of crack growth under the action of long-term static and cyclic pressures, soil corrosion, hydrogenation, and degradation of the materials. The idea of these methods is described in the next section.

Evaluation of the Residual Service Life of a Pipe of Gas Pipeline under the Action of Static Pressure and Soil Corrosion with Regard for the Degradation of Material

We studied a pipe made of Kh52 steel with the wall thickness $h = 12$ mm. The pipe is subjected to the action of long-term static pressure of natural gas $p = 8$ MPa and weakened by an external surface semielliptical crack with semi-axes a and b (Fig. 1).

It is assumed that the soil medium penetrates into the crack and promotes its stress-corrosion propagation. As a result of the long-term operation under the indicated conditions, the material of the pipe degrades simultaneously with the process of crack propagation. It is necessary to determine the time $t = t_*$ for which the crack grows through the pipe wall ($b = h$) and the pipe depressurizes.

Under conditions of long-term static loading and soil corrosion, this crack mainly propagates with a constant velocity V_k [7]. In this case, $V_k(0) = 1.03 \cdot 10^{-3}$ m/yr and $V_k(30) = 8.03 \cdot 10^{-3}$ m/yr for the as-received pipe and the pipe after operation for 30 yr, respectively. On the basis of these data, for any duration of operation of the pipe, the velocity $V_k \approx V_k(t)$ can be approximately found as follows [2]:

$$V_k(t) = 10^{-3}[1.03 + 0.23(t_0 + t)] \quad (\text{m/yr}), \quad (1)$$

where t_0 is the initial period of operation of the pipe prior to the time of the prediction of the service life of gas pipeline.

The posed problem is solved within the energy approach [8]. It is reduced to the following relations:

$$\frac{\partial \rho}{\partial t} = V_k(t) \sqrt{1 + \rho^{-2} \frac{\partial^2 \rho}{\partial \alpha^2}}, \quad t = 0, \quad \rho(0, \alpha) = \rho_0(\alpha), \quad t = t_*, \quad \rho\left(t_*, \frac{\pi}{2}\right) = h, \quad (2)$$

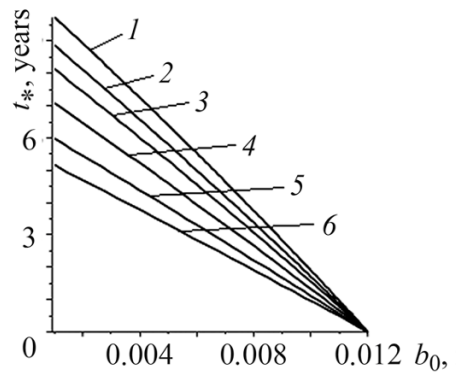


Fig. 2. Dependences of the residual service life of the pipe t_* on the initial crack depth b_0 and the initial time of its operation t_0 : (1) $t_0 = 0$; (2) 4; (3) 8; (4) 15; (5) 25; (6) 35 yr.

where α and ρ are coordinates of the polar system $O\alpha\rho$ (Fig. 1). These relations specify the kinetic system of crack contours. For the approximate solution of the problem, we act as follows: Since the initial crack is semielliptic and its growth rate is constant, it is possible to assume [8] that the crack propagates in the same way as an elliptic crack. Hence, we assume that the moving crack has elliptic configuration. Therefore, the solution of problem (2) can be reduced to the following system of ordinary differential equations:

$$\frac{da}{dt} = 10^{-3}[1.03 + 0.23(t_0 + t)], \quad (3)$$

$$\frac{db}{dt} = 10^{-3}[1.03 + 0.23(t_0 + t)], \quad (3)$$

$$t = 0, \quad a(0) = a_0, \quad b(0) = b_0, \quad t = t_*, \quad a(t_*) = a_*, \quad b(t_*) = h. \quad (4)$$

We solve this system and obtain the following relations for the determination of the kinetics of variations of the semiaxes of contours as functions of time:

$$a(t) = a_0 + 10^{-3}(1.26t + 0.23tt_0 + 0.23t^2), \quad (5)$$

$$b(t) = b_0 + 10^{-3}(1.26t + 0.23tt_0 + 0.23t^2).$$

Substituting the second relation in (5) in relation (4), we get

$$t_*^2 + (103 + 23t_0)t_* - 10^5(h - b_0) = 0. \quad (6)$$

Thus, for the residual service life of the pipe, we obtain

$$t_* = \sqrt{0.25(103 + 23t_0)^2 + 10^5(h - b_0)} - 0.5(103 + 23t_0). \quad (7)$$

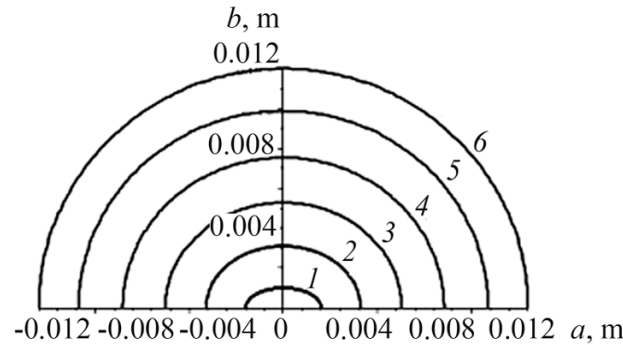


Fig. 3. Kinetics of growth of the crack contours for different times: (1) $t = 0$; (2) 2; (3) 4; (4) 6; (5) 9; (6) 9.76 yr.

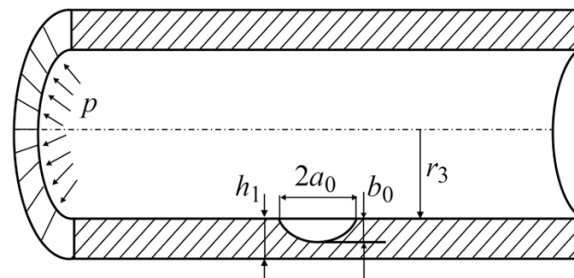


Fig. 4. Loading of the pipe of oil pipeline weakened by an internal surface crack.

By using formula (7), we plotted (Fig. 2) the dependences of the residual service life of the pipe t_* on the initial crack depth b_0 and the time of its operation t_0 . In Fig. 3, we present the system of kinetic contours for a propagating semielliptic crack starting from the initial values $a_0 = 0.002$ m, $b_0 = 0.001$ m, and $t_0 = 0$. This system of contours is constructed for the time interval $0 \leq t \leq t_*$, where the time is given by relation (7): $t_* = 9.76$ yr. It was shown that the residual service life of the pipe strongly depends on the initial time of its operation t_0 and the elliptic contour of the crack eventually approaches a circular contour.

Diagnostics of the Residual Service Life of the Pipe of Oil Pipeline with Turbulent Flow of Oil with Regard for the Degradation of Its Material

It is known [9] that the oil pipelines are, as a rule, equipped with external isolation and systems of electrochemical protection. Therefore, their fracture starts (most often) from the inner surface of the pipe (see Fig. 4), where surface cracks are initiated as a result of degradation of the material under the action of loads. If the oil flow is turbulent, then the pipe is subjected to the action of two-frequency loading [9, 10]: a high-frequency ($\omega_1 = 0.6 \text{ sec}^{-1}$; the period of a cycle $T_1 \approx 1.7$ sec) load caused by the turbulence of the oil flow and a low frequency ($\omega_2 = 2.1 \cdot 10^{-6} \text{ sec}^{-1}$; the period of a cycle $T_2 \approx 476,190$ sec) load caused by the shutdowns of the process of pumping of oil (switching-off of the pumps, closure of blinds, etc.). In other words, one low-frequency cycle includes N_1 high-frequency oscillations, where

$$N_1 = \frac{\omega_1}{\omega_2} \approx 28 \cdot 10^4. \quad (8)$$

This should be taken into account in finding the residual service life of the pipe. For this purpose, we use the energy approach [8, 11] whose essence can be described as follows:

We study a pipe of oil pipeline whose radius $r_3 = 710$ mm and wall thickness $h_1 = 18.7$ mm (Fig. 4). The pipe is made of Kh70 steel and weakened by an internal surface semielliptic crack. A turbulent flow of oil inside the pipe occurs under a pressure $p \approx 4$ MPa with variations $\Delta p \approx 0.25$ MPa caused by the turbulence. The level of pressure in the pipe varies according to a two-frequency law. It is necessary to find the residual service life of the pipe, i.e., the number of low-frequency loading cycles $N = N_*$ after which the crack contour approaches the outer surface of the pipe, which leads to its depressurization.

Parallel with the energy approach, for the approximate evaluation of the residual service life of the pipe with an accuracy sufficient for engineering calculations, we used the method of equivalent areas. With the help of this method, the solution of the problem is reduced to the following mathematical model [10]:

$$\frac{d\rho}{dN} = \frac{\alpha(1-R)^4 [K_{I\max}^4(1+N_1(1-R_1)^4) - K_{th}^4]}{K_{fC}^2 - K_{I\max}^2}, \quad (9)$$

$$N = 0, \quad \rho(0) = \rho_0 = \sqrt{a_0 b_0}, \quad N = N_*, \quad \rho(N_*) = h_1.$$

Here, ρ is the radius of a semicircular crack whose area is equal to the area of the actual crack; α , K_{th} , and K_{fC} are the characteristics of the kinetic diagram of fatigue crack growth [10]; R and R_1 ($R = 0.1$; $R_1 = 0.94$) are the load ratios for the low- and high-frequency loads, respectively, and $K_{I\max}$ is the maximum value of the stress intensity factor in a cycle and on the contour of a semicircular crack [8]:

$$K_I = 0.7\sigma\sqrt{\pi h_1 \varepsilon} (1 + 0.32\varepsilon^2)(1.04 + 0.23\varepsilon^2 - 0.11\varepsilon^4); \quad (10)$$

$$\varepsilon = \frac{\rho}{h_1}; \quad \sigma = pr_3 h_1^{-1}.$$

At the same time, the material of the pipe of oil pipeline degrades in the course of operation and under the action of aggressive factors. In other words, the parameters α , K_{th} , and K_{fC} depend on the duration of operation t (number of loading cycles N) and the fatigue-fracture resistance of the material becomes lower. Since the pipe is made of Kh70 steel, the time dependence of these characteristics is regarded as linear because their variations in the course of operation for 30 yr are insignificant [12] (Fig. 5). Therefore, we can write

$$\alpha(N) = 10^{-8} [1.6 - 2 \cdot 10^{-4} (N + N_0)] \text{ (MPa)}^{-2} \text{ (cycle)}^{-1}; \quad (11)$$

$$K_{th}(N) = 9.1 - 1.3 \cdot 10^{-3} (N + N_0) \text{ MPa} \sqrt{\text{m}};$$

$$K_{fC}(N) = 98 - 1.3 \cdot 10^{-2} (N + N_0) \text{ MPa} \sqrt{\text{m}}.$$

Here, N_0 is the initial operation time (number of loading cycles) of the pipe prior to the time of prediction of the residual service life of the oil pipeline. We now substitute relations (10) and (11) and the parameters of geometry and loading in Eq. (9). As a result, we get a new differential equation without constant coefficients that can be numerically integrated [13, 14]. We represent the solution of the posed problem in the form of a plot (Fig. 6).

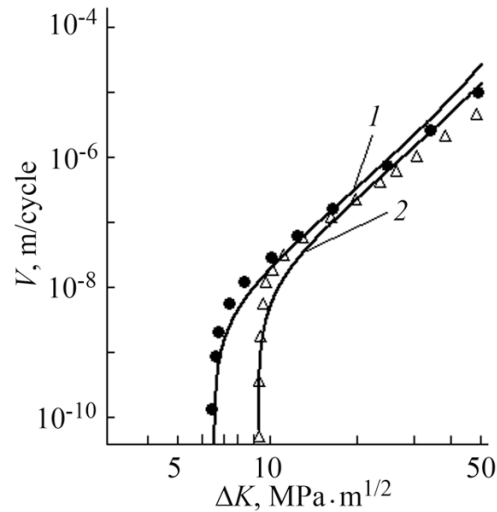


Fig. 5. Influence of the operation for 30 yr on the fatigue-fracture diagram of Kh70 steel: (1), (●) pipe after operation; (2), (△) pipe from the stock [12].

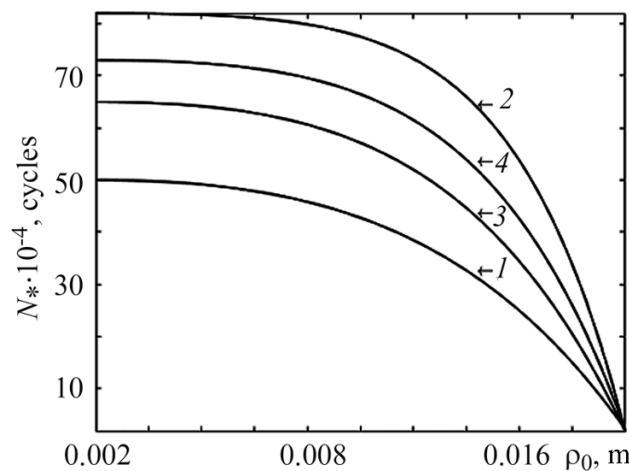


Fig. 6. Dependences of the residual service life N_* of the pipe on the initial crack size ρ_0 and the initial time of its operation N_0 : (1) $N_0 = 1300$; (2) 0; (3) 650; (4) 350 cycles.

It is easy to see that the residual service life of the oil pipeline becomes much shorter as the size of initial defect and the initial period of operation increase.

Evaluation of the Residual Service Life of the Pipe of Oil Pipeline under the Conditions of Variable Oil Flow and Hydrogenation with Regard for the Degradation of the Material

We studied a pipe of oil pipeline made of Kh60 steel and weakened by an external surface semielliptic crack. The crack is hydrogenated and the aggressive soil medium penetrates into the crack (Fig. 1). The geometric parameters and the load applied to the pipe are the same as in the above-described case. It is necessary to determine the residual service life of the pipe $N = N_*$ with regard for the load, influence of the corrosive media, hydrogenation, and the degradation of steel with time.

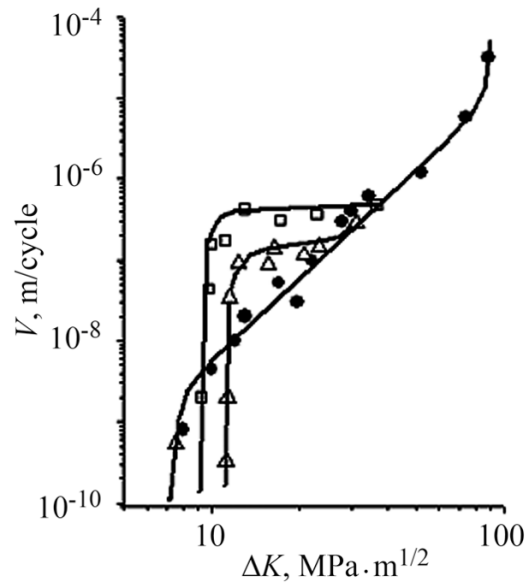


Fig. 7. Influence of operation on the fatigue-fracture diagram of X60 steel in a soil medium under the conditions of hydrogenation [12]: (◆) after operation, air; (□) and (Δ) pipe after operation and pipe from the stock, respectively, in the soil medium under the conditions of cathodic polarization E_n .

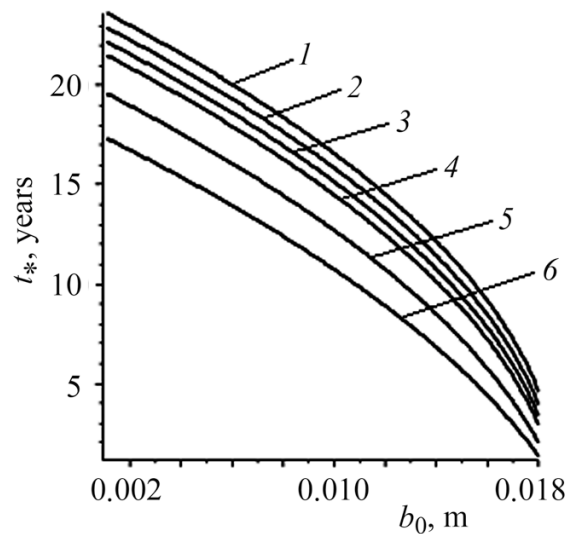


Fig. 8. Dependences of the residual service life t_* of the pipe on the initial crack depth b_0 and the initial period of its operation N_0 : (1) $N_0 = 0$ cycles; (2) 50; (3) 100; (4) 150; (5) 300; (6) 500.

The diagrams of fatigue crack growth plotted for the pipes after operation and from the stock (Fig. 7) differ from the diagrams presented in Fig. 5 both qualitatively and quantitatively. Thus, in Fig. 7, we observe the appearance of a plateau on which the crack growth rate V is constant for the variable stress intensity factors. On this plateau, the crack growth rates for the materials of the analyzed pipes are as follows:

$$V(0) \approx 1.4 \cdot 10^{-7} \text{ m/cycle} \quad \text{and} \quad V(30) \approx 5.6 \cdot 10^{-7} \text{ m/cycle}. \quad (12)$$

The difference between these rates is insignificant. Therefore, for any operation time, the rate $V(N)$ can be approximately represented as a function of the number of cycles as follows:

$$V(N) \approx 10^{-7}[1.4 + 0.14(N_0 + N)] \text{ m/cycle.} \quad (13)$$

Then we solve the problem in the same way as above. As a result, for the residual service life of the pipe of oil pipeline, with regard for the indicated operational factors and the process of degradation of material, we obtain

$$N_* = \sqrt{(10 + N_0)^2 + 14.3 \cdot 10^7(0.0187 - b_0)} - 10 - N_0 \text{ cycles,} \quad (14)$$

$$t_* = 0.015[\sqrt{(10 + N_0)^2 + 14.3 \cdot 10^7(0.0187 - b_0)} - 10 - N_0] \text{ yr.}$$

Thus, it is demonstrated (see Fig. 8) that the residual service life of the pipe significantly decreases as the initial crack depth b_0 and the initial period of operation of the pipe N_0 increase.

CONCLUSIONS

We propose new methods for the evaluation of the service life of the pipes of oil and gas pipelines containing surface cracks under the action of a long-term constant gas pressure in gas pipelines, variable (as a function of time) pressure in oil pipelines, hydrogenation, and soil corrosion with regard for the degradation of their materials in the course of time. We computed the residual service lives of pipes of oil and gas pipelines made of Kh52, Kh60, and Kh70 steels.

The present work was partially supported by the Project G5055 of the NATO Program in Science for Peace and Security. The article contains the results of investigations supported by the grant of President of Ukraine within the Competitive Project F75/143-2018 of the State Foundation for Fundamental Research.

REFERENCES

1. V. N. Chuvil'deev and N. N. Viryasova, *Deformation and Fracture of Structural Materials: Problems of Aging and Service Life* [in Russian], V. N. Chuvil'deev (editor), Nizhnii Novgorod State University, Nizhnii Novgorod (2010).
2. Ye. I. Kryzhaniv's'kyi and H. M. Nykyforchyn, *Hydrogen-Corrosion Degradation of Oil and Gas Pipelines and Its Prevention* [in Ukrainian], V.V. Panasyuk (editor), Ivano-Frankiv's'k National Technical University of Oil and Gas, Ivano-Frankiv's'k (2010).
3. O. Ye. Andreikiv, V. R. Skal's'kyi, V. K. Opanasovych, I. Ya. Dolins'ka, and I. P. Shtoiko, "Determination of the period of subcritical growth of creep-fatigue cracks under block loading," *Mat. Met. Fiz.-Mekh. Polya*, **58**, No. 1, 84–91 (2015); **English translation:** *J. Math. Sci.*, **222**, No. 2, 103–113 (2017).
4. O. Ye. Andreikiv, I. Ya. Dolins'ka, V. Z. Kukhar, and I. P. Shtoiko, "Influence of hydrogen on the residual service life of a gas pipeline in the maneuvering mode of operation," *Fiz.-Khim. Mekh. Mater.*, **51**, No. 4, 59–66 (2015); **English translation:** *Mater. Sci.*, **51**, No. 4, 500–508 (2016).
5. O. Ye. Andreikiv, H. M. Nykyforchyn, I. P. Shtoiko, and A. R. Lysyk, "Evaluation of the residual life of a pipe of oil pipeline with an external surface stress-corrosion crack for a laminar flow of oil with repeated hydraulic shocks," *Fiz.-Khim. Mekh. Mater.*, **53**, No. 2, 80–88 (2017); **English translation:** *Mater. Sci.*, **53**, No. 2, 216–226 (2017).
6. O. Ye. Andreikiv, O. K. Raiter, and I. P. Shtoiko, "Determination of the period of subcritical growth of an internal surface stress-corrosion crack in a pipe of pipeline for the turbulent flow of oil with hydraulic shocks," *Fiz.-Khim. Mekh. Mater.*, **53**, No. 6, 88–93 (2017); **English translation:** *Mater. Sci.*, **53**, No. 6, 842–848 (2018).

7. G. Gabetta, H. M. Nykyforchyn, E. Lunarska, P. P. Zonta, O. T. Tsyurulnyk, K. Nikiforov, M. I. Hredil, D. Yu. Petryna, and T. Vuherer, "In-service degradation of gas trunk pipeline X52 steel," *Fiz.-Khim. Mekh. Mater.*, **44**, No. 1, 88–99 (2008); **English translation:** *Mater. Sci.*, **44**, No. 1, 104–115 (2008).
8. O. Ye. Andreikiv and N. B. Sas, "Subcritical growth of a plane crack in a three-dimensional body under the conditions of high-temperature creep," *Fiz.-Khim. Mekh. Mater.*, **44**, No. 2, 19–26 (2008); **English translation:** *Mater. Sci.*, **44**, No. 2, 163–174 (2008).
9. L. F. Zaitsev, *Control over the Modes of Operation of Oil Mains* [in Russian], Nedra, Moscow (1982).
10. O. Ye. Andreikiv, Ya. L. Ivanytskyi, Z. O. Terletska, and M. B. Kit, "Evaluation of the durability of a pipe of pipeline with surface crack under biaxial block loading," *Fiz.-Khim. Mekh. Mater.*, **40**, No. 3, 103–108 (2004); **English translation:** *Mater. Sci.*, **40**, No. 3, 408–415 (2004).
11. O. Ye. Andreikiv and M. B. Kit, "Determination of the period of subcritical crack growth in structural elements subjected to two-frequency loads," *Mashynoznavstvo*, No. 2, 3–7 (2006).
12. O. Ye. Andreikiv, O. V. Hembara, O. T. Tsyurul'nyk, and L. I. Nyrkova, "Evaluation of the residual lifetime of a section of main gas pipeline after long-term operation," *Fiz.-Khim. Mekh. Mater.*, **48**, No. 2, 103–110 (2012); **English translation:** *Mater. Sci.*, **48**, No. 2, 231–238 (2013).
13. J. R. Dormand and P. J. Prince, "A family of embedded Runge–Kutta formulae," *J. Comp. Appl. Math.*, **6**, 19–26 (1980).
14. L. F. Shampine and M. W. Reichelt, "The MATLAB ODE Suite," *SIAM J. Sci. Comput.*, **18**, 1–22 (1997).