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CORROSION OF INDUSTRIAL GAS PIPELINES UNDER THE ACTION OF FORMATION WATERS

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Summary. *The state of pipeline after the long time of operation is studied. Major factors are determined, influencing nature and rate of the passage of the processes of the internal corrosion of pipelines – presence of perceptible mechanical stresses, chemical composition and the motion of corrosive environment. The results obtained allow a more accurate and accurate prediction of the life and residual life of industrial pipelines, taking into account the influence of mechanical and corrosion factors.*
Key words*: industrial gas pipelines, formation water, intrinsic corrosion, corrosion-mechanical tests.*

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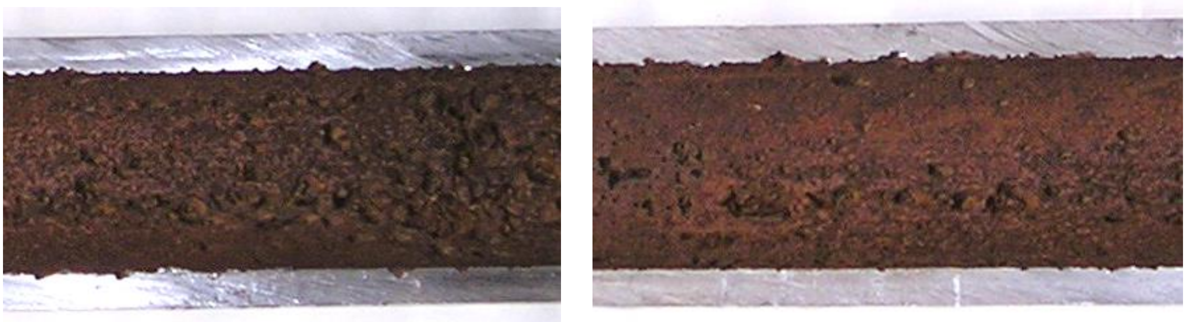
Statement of the problem. Ukraine's energy independence is one of the priorities for the development of its oil and gas complex. It is impossible to achieve it without increasing the production of gas and gas condensate, and at the same time reducing their losses at the stage of transportation by industrial pipelines from the place of extraction to the compressor stations (CS). One of the main causes of such losses is the failure of pipelines due to corrosion damage.

The condition of the industrial pipeline after a long period of operation was studied. It is revealed that at practically absent corrosion damages of an external surface (Fig. 1, d), internal corrosion practically destroyed a pipe from the inside (Fig. 1, a, b, c). It is also easy to see that the top is destroyed more than the bottom. In our view, this is due to the influence of a mechanical factor, and the stress state is heterogeneous.



a b

c d

Figure 1. Characteristics of corrosion damages of the inner and outer surfaces of the pipeline:
a – the upper inner part; b – lower inner part; c – the middle inner part; d is the outer surface

Analysis of the available investigations. Under the action of the soil array, there was a gradual bend of the pipeline. Its upper inner part was in the area of stretching, the lower – compression. This is confirmed by the appearance of corrosion damage to the central inner part. It is the least damaged because it is close to the neutral line, where the influence of stresses is the least. Finally, the outer part is practically intact.

Therefore, the cause of the damage is the corrosive action of the formation water entering the pipeline together with the gas condensate and. later, the groundwater acting on the transport route from the extraction site to the CS is reinforced by a mechanical factor, in other words internal stress corrosion. Moreover, when transporting gas condensate by pipeline, the corrosive medium moves with the speed of the transported product, which, as is known from the literature, can accelerate the rate of corrosion processes by up to 8 times, due to complication of passivation of the pipeline surface due to the deterioration of the adsorption of passive products [1]. The newly formed passivation film is washed away by the transported product and the surface becomes vulnerable again [2–3].

Statement of the task. The research object selected seamless steel pipes with a wall thickness of 17 mm, which are used for the construction of industrial pipelines.

To investigate corrosion processes under stress, we used the computer-aided KN-1 installation [4], developed on the basis of the MV-1K installation [5]. Testing of samples from piping material in air and in liquid working environments was performed in static load mode with a pure bend with automatic registration of the deflection of the sample and change of electrode potential by computer using 24-bit analog-to-digital conversion.

In order to simulate the stress-corrosion processes in the most accurate way, we performed an analysis of reservoir water and groundwater at different stages of gas condensate transportation. On this basis, we selected 3 model environments that correspond to the formation water of the well, palletized at the stage of transportation and selection at the compressor station (Table 1).

Table 1

Composition of model environments

Model environment (ME)	Origin of sample	pH	Concentration, mmol/l		
			SO_4^{2-}	NO_3^-	Cl^-
1	selection on the COP	6,2	2,8	4,8	4,0
2	MPKG-4 formation water	6,0	3,6	7,6	5,1
3	pallet water	6,1	7,5	5,3	5,1

Prolonged action on the pipeline of loads and impacts in the soil massif causes various structural changes, including deformation and relaxation of stresses. Therefore, studying the patterns of changes in the physical and mechanical properties of the pipeline material in the process of long-term operation will allow more accurately predict the residual life of the existing pipelines. In modern conditions, when a considerable part of pipelines is operated for 15–20 years and is close, according to preliminary data, to the exhaustion of its resource of work, the study of their corrosion-mechanical behavior is an urgent scientific task [4].

For the construction of nominal deformation diagrams, a direct stepped load (unloading) of the sample (Fig. 2) was used with a clean bend, when the load transferred to it did not decrease with decreasing resistance [5, 6].

With increasing or decreasing the load by one degree, the nominal voltages changed by $\Delta\sigma$ = 20 MPa during the time $t_{n\text{-}p}$ = 1 s. Exposure time at each stage was t_b = 19 s, and the total time $\Delta t = t_{n\text{-}p} + t_b$ = 20 s. This mode of loading allows to take into account the lag of deformation from stress in time and to study in depth the processes of strain hardening and creep [7].

Experimental studies of the creep phenomenon, the results of which have recently been increasingly used in engineering calculations and in the optimization of pipeline structures, are conducted mainly in tensile. Under conditions of inhomogeneous stress state at T ≤ 293 K, the creep of the material of industrial pipelines has not been sufficiently studied, mainly theoretically, although it is known that various deformation effects are observed when the conditions of loading of pipe steels change, and any theoretical prediction can be considered correct only then has experimental confirmation.

Table 2

Physico-mechanical characteristics of pipeline material in model environments

Characteristics of the material	Environment			
	Air	ME1	ME2	ME3
Young's modulus, E·10–5, MPa	2,023	2,064	2,063	1,97
Yield strength, MPa	250	245	245	245
Tensile strength, MPa	410	400	400	400

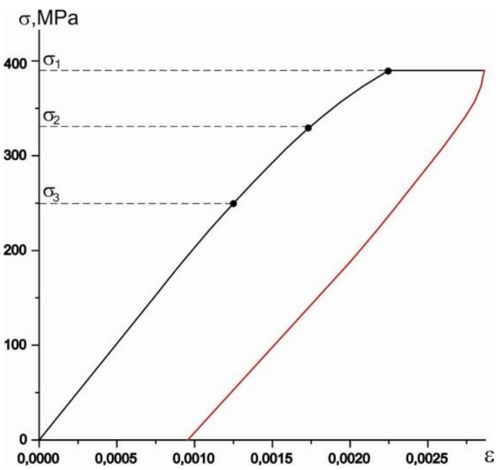


Figure 2. Nominal deformation diagram of pipeline steel samples in air

Creep is often seen as slow metal fluidity. As is known, the basis of the theory of plastic flow is the idea of the surface of fluidity. In the process of static bending there is a regular movement of the surface of fluidity, that is, its evolution.

The characteristic creep curves in the coordinates of the creep increment $\Delta\varepsilon_c$ – time t are shown in Figure 3. The duration of the air tests was determined by the nature and kinetics of the process on a case-by-case basis, which allowed a relatively short time to perform a series of experiments and to determine the parameters of the low-temperature creep region (LCR).

The total deformation gain Δε for time t for a given stress range can be determined by the formula:

$$\Delta\varepsilon = \Delta\varepsilon_{el} + \Delta\varepsilon_{pl} + \Delta\varepsilon_c,$$

where $\Delta\varepsilon_{el}$ and $\Delta\varepsilon_{pl}$ – respectively the increment of elastic and plastic deformation when reaching a given level of stresses, $\Delta\varepsilon_c$ – the creep gain.

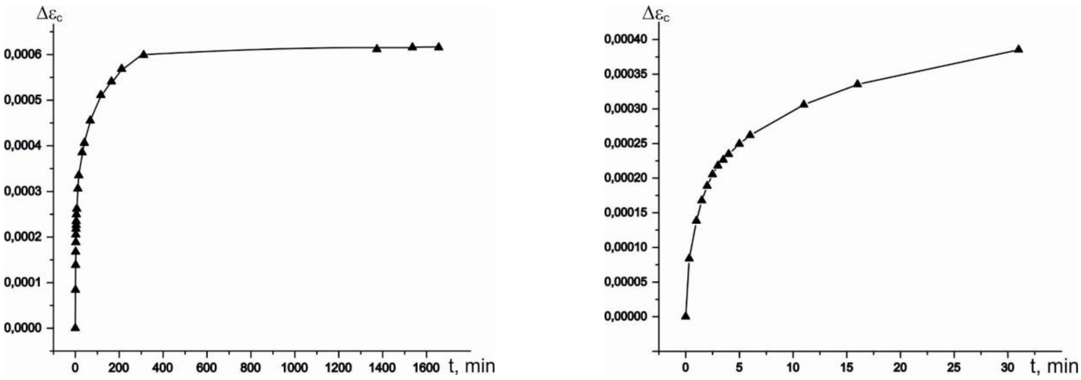


Figure 3. Creep kinetics of air pipeline steel: general (a) and initial stage (b); T = 293 K; σ = 390 MPa

It was also established that the creep of the base metal in the corrosive-active medium, as well as in the air, is of a stage character (Fig. 4–6). The influence of the environment is noticeable both at the unsteady stage and at the steady creep stage. As shown by our studies, the pipeline steel exhibits the highest tendency for low-temperature corrosion creep in ME2, the lowest – in ME3 (Table 1).

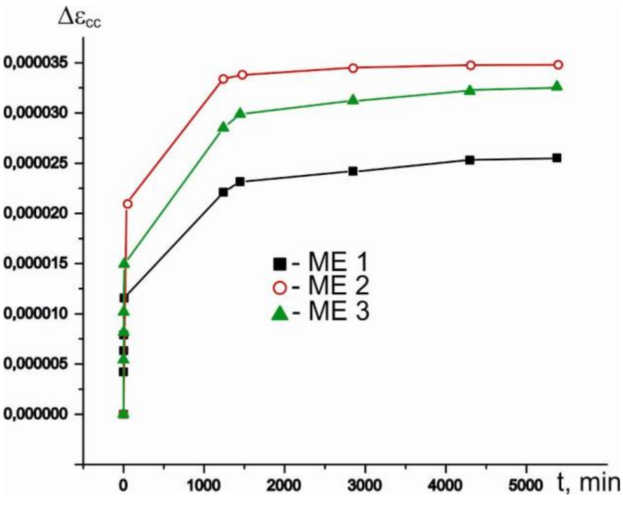


Figure 4. Piping material creep at 250 MPa rated voltage

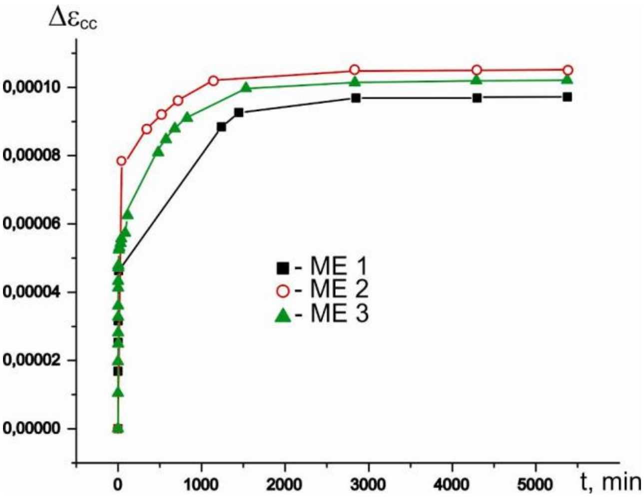


Figure 5. Creep curves of the pipeline material at 335 MPa

The duration of the first stage depends more on the magnitude of the nominal stresses and less on the chemical composition of the medium (Fig. 4–6).

The study of the dependences of the corrosion creep increase on the magnitude of the nominal stresses and the chemical composition of the medium (Fig. 7) makes it possible to conclude that their greatest synergistic effect is observed in ME2, the smallest in ME1.

That is, the greatest danger of loss of bearing capacity of the pipeline during operation is in ME2, which corresponds to the formation water of the well (Table 1).

In order to better study the chemistry of the process of internal stress corrosion of the pipeline steel and to determine the most dangerous, from the chemical point of view, the operating environment, we investigated the kinetics of the electrode potential. It is known that the lower the potential of the metal and the faster the process of decomposition. the greater the likelihood of corrosion processes and, consequently, the risk of corrosion [8–10].

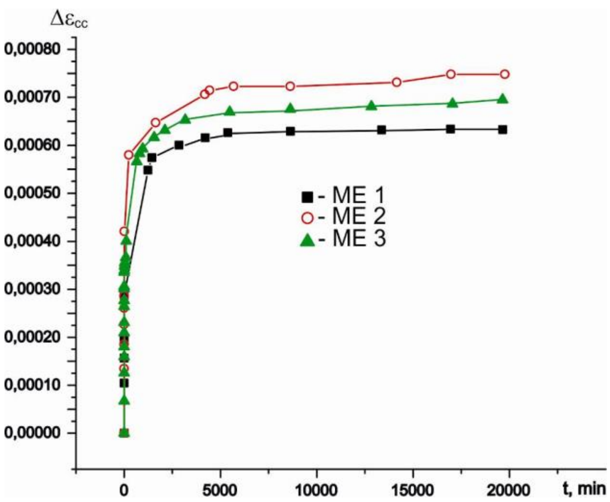
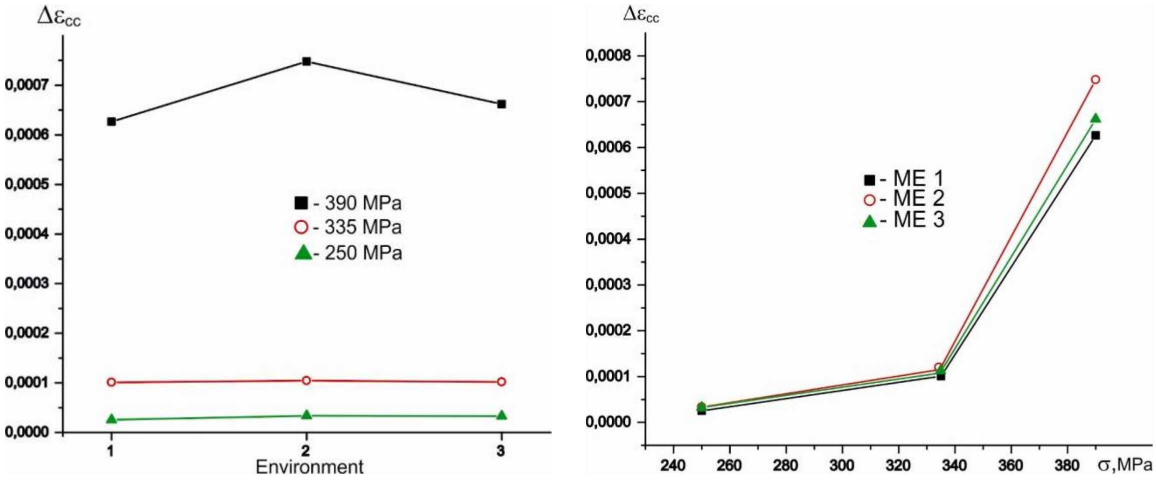


Figure 6. Pipeline material creep kinetics at rated voltages of 390 MPa



a b

Figure 7. Dependence of creep growth on stress level (a) and chemical composition of medium (b); t = 5000 min

The dependence of the electrode potential of the samples on the chemical composition of the medium at different nominal voltages is shown in Figure 8–10.

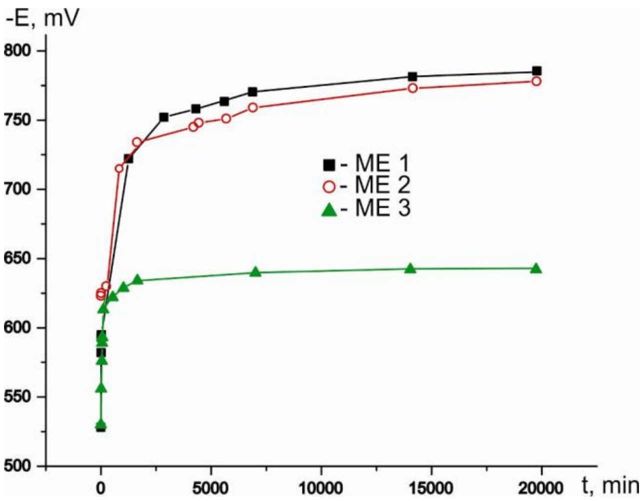


Figure 8. Potential-time curves at σ = 1.6 σ0.2 in model environments

As we can see, the synergistic effect of corrosive-active medium and applied mechanical stresses is also shown here.

To conclude on the aggressiveness of each medium, we compare the rate of decomposition of the electrode potential of the pipeline steel in them. From Figure 8–10 we see that at σ = 1.6 σ0.2 the decomposition rate in ME1 and ME2 is practically equal, with a slight advantage in ME2, in ME3 it is much lower.

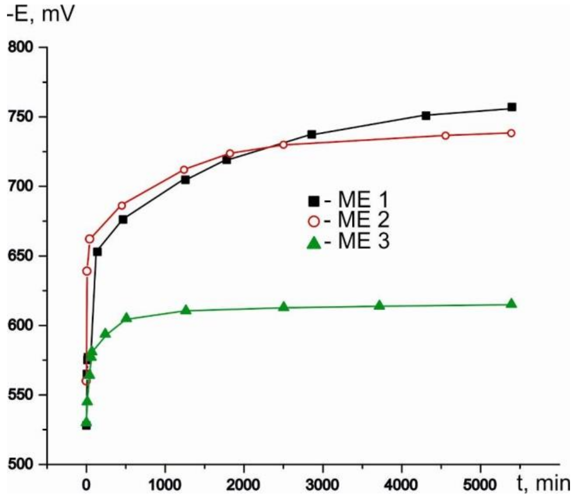


Figure 9. Potential-time curves at $\sigma = 1.35\ \sigma_{0.2}$ in model environments

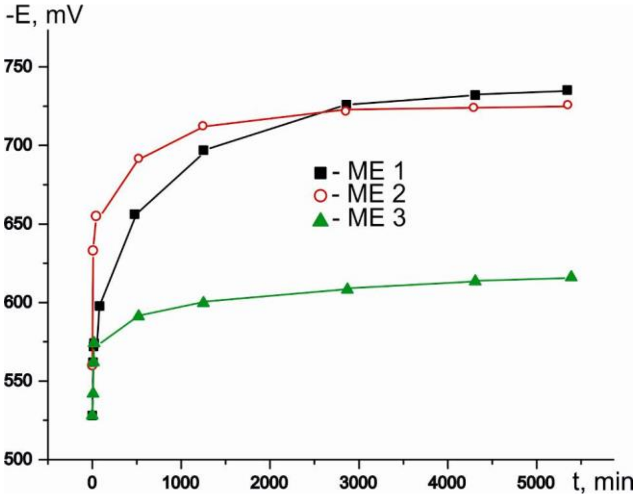


Figure 10. Potential-time curves at $\sigma = 1.05\ \sigma_{0.2}$ in model environments

Now let's examine the effect on the process of refinement of a mechanical factor. We compare the kinetics of the electrode potential at $\sigma = 1.6\ \sigma_{0.2}$, $1.35\ \sigma_{0.2}$, and $1.05\ \sigma_{0.2}$. We see that as the level of nominal voltages decreases, the rate of decomposition process in ME2 is practically unchanged, whereas in ME3 and especially in ME1 it is significantly reduced.

Therefore, ME2 is the most dangerous environmentally chemical environment, since the process of decomposition in it is controlled by the corrosion factor. This means that even with a minimum level of mechanical stress, the corrosion will be quite intense.

In ME1, we observe a mixed control with an emphasis on the mechanical factor. From a chemical point of view, it is, by the way, the safest of our environments

In ME3, the situation is almost the same, but the refinement itself is less intense. In the corrosive activity it occupies an intermediate place.

The dependence of the stabilization potential of the steel pipeline on its stress-strain state is illustrated in Figure 11.

In order to check the conclusions made and to determine the real degree of danger during the operation of the pipeline in each of the three MS, we studied the kinetics of corrosion processes in them and determined the velocity of corrosion and the reduction of the thickness of the pipe wall. The corresponding curves are presented in Figure 12–13.

As we predicted, based on the kinetics of the potential, the highest velocity is observed in ME2, the lowest – in ME1. The low corrosion rate in the latter confirms our assumption that the rapid decrease in electrode potential in ME1 is mainly due to the plastic flow processes in the pipeline steel, which is inevitably accompanied by the formation of juvenile surfaces and sub-microcracks, which have a freshly formed surface; as well as the highest relative content of chloride ions that impedes its rapid passivation.

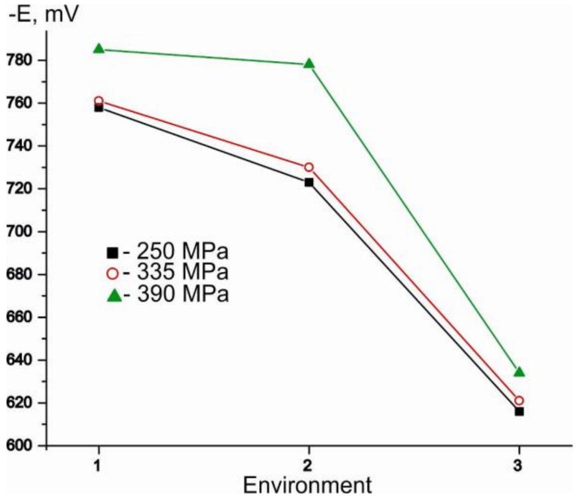


Figure 11. Impact of a mechanical factor on the stabilization potential of a pipeline steel

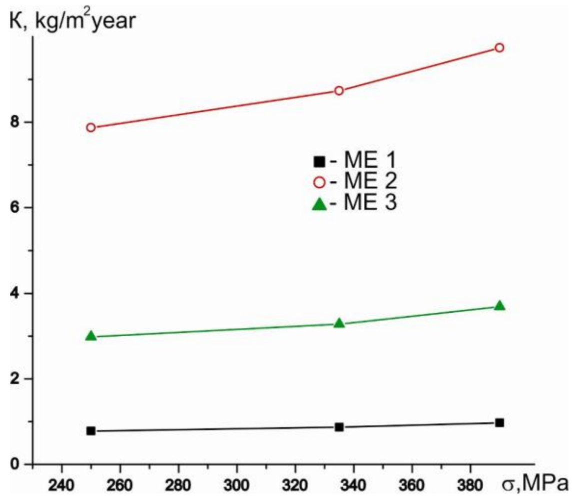


Figure 12. Dependence of corrosion rate on the chemical composition of the medium

Regarding the reduction of the wall thickness of the pipeline, we can see here (Fig. 13) that, even with the minimum stress level, it can reach from 0.125 to 1.25 mm/year depending on the chemical composition of the medium and the level of nominal stresses.

The dependences of the general corrosion rate and the reduction of the wall thickness of the pipeline on σ are shown in Figure 14 and 15.

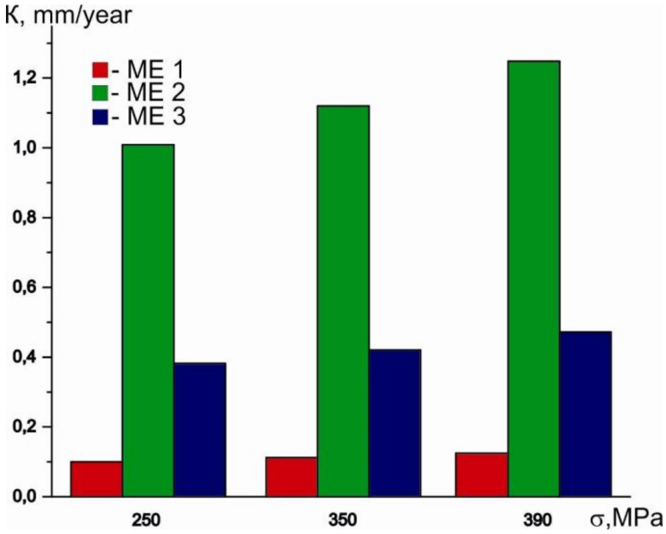


Figure 13. Dependence of reducing the thickness of the pipeline wall on the chemical composition of the medium

It is established that with the increase of the value of the nominal stresses from 1.05 $\sigma_{0.2}$ to 1.6 $\sigma_{0.2}$, the increase of the general corrosion rate in model media can reach 25%.

Thus, in no case can a mechanical factor be neglected when calculating the residual life of existing pipelines and designing new ones.

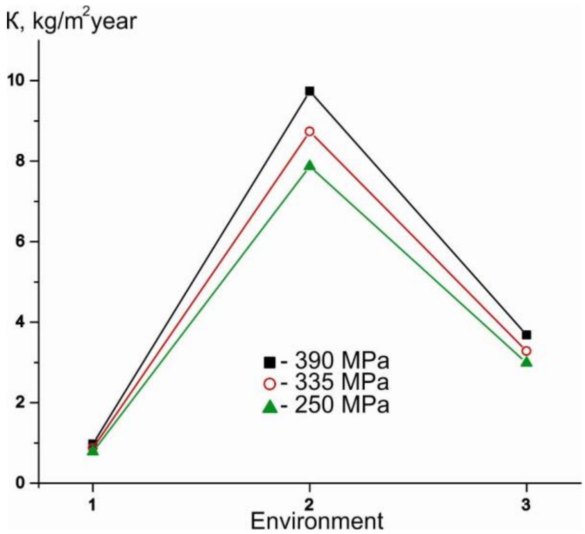


Figure 14. Dependence of the reduction of the wall thickness of the pipeline on the level of rated voltages

It is also necessary to take into account the constant intensive movement of the corrosive medium, in which:

- there is a constant flushing of insoluble corrosion products, ie the passivation of the surface deteriorates;

- there is a tendency to localize corrosion processes because the initially affected area cannot be passivated, and therefore constantly has less potential than neighboring unaffected sites;
- a galvanic element is formed in which the affected area becomes an anode and the unoccupied one becomes a cathode;
- the rate of local corrosion can be 2–8 times higher than the total rate.

Given that under unfavorable conditions, which we must take into account, the mechanical factor and the environmental factor will mutually enhance the corrosion processes, it is easy to calculate that the rate of local corrosion, and, consequently, the magnitude of the reduction in wall thickness can increase by 2.5–10 times compared to the ones shown in Figure 12–15.

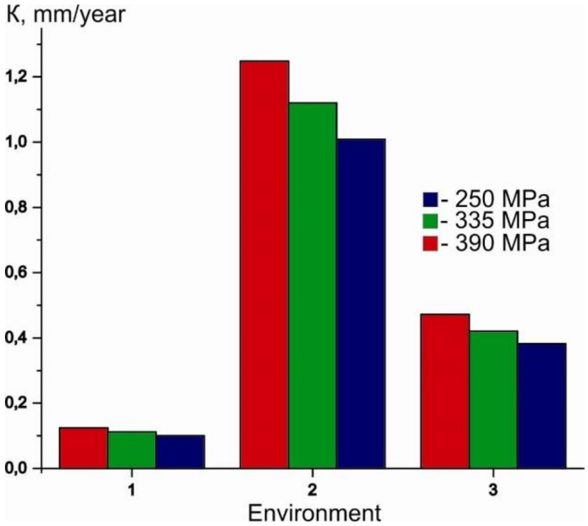


Figure 15. Dependence of the reduction of the wall thickness of the pipeline on the level of rated voltages

The results obtained allow us to more accurately and more accurately predict the life and residual life of industrial pipelines, taking into account the influence of mechanical and corrosion factors.

Conclusions. The main factors that determine the nature and speed of the internal corrosion processes of pipelines, namely, the presence of tangible mechanical stresses, chemical composition and movement of the corrosive environment, are identified. It is shown that the most dangerous corrosion plan is ME2 (formation water), that is, the highest probability of failure of the pipeline exists in the first transport section – in the immediate vicinity of the well. It is found that even in the safest environment ME1 – liquid sample from CS the corrosion rate is quite significant and the reduction of wall thickness, taking into account the localization of the process, can be from 1 to 1.25 mm/year.

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УДК 620.179

ВПЛИВ ПЛАСТОВИХ ВОД НА КОРОЗІЮ ПРОМИСЛОВИХ ГАЗОПРОВОДІВ

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Резюме. *Енергетична незалежність України – один із пріоритетів розвитку її нафтогазового комплексу. Досягнення її неможливе без збільшення видобутку газу і газового конденсату й одночасного зменшення їх втрат на стадії транспортування промисловими трубопроводами від місця видобування до компресорних станцій (КС). Одна із основних причин таких втрат – вихід з ладу трубопроводів через корозійні ураження. Вивчено стан промислового трубопроводу після тривалого періоду експлуатації. Виявлено, що при практично відсутніх корозійних ураженнях зовнішньої поверхні внутрішня корозія практично зруйнує трубу зсередини. Об'єктом досліджень вибрано безшовні труби товщиною стінки 15 мм, які використовуються для будівництва промислових трубопроводів. Випробовування зразків із матеріалу трубопроводів на повітрі та в рідких робочих середовищах проводили в режимі статичного навантаження чистим згином із автоматичною реєстрацією прогину зразка та зміни електродного потенціалу за допомогою ЕОМ, використовуючи 24-бітне аналого-цифрове перетворення. Використано плоскі зразки, виготовлені за розробленою в ІФНТУНГ технологією з матеріалу різних ділянок лінійної частини трубопроводу. Встановлено, що повзучість основного металу в корозійно-активному середовищі, як і на повітрі, носить стадійний характер. Вплив середовища відчутний як на стадії неусталеної, так і усталеної повзучості. Як показали дослідження, найбільшу схильність до низькотемпературної корозійної повзучості сталь трубопроводу проявляє у МС2, найменшу – у МС3. З метою кращого вивчення хімізму процесу внутрішньої стрес-корозії сталі трубопроводу та визначення найнебезпечнішого, з хімічної точки зору, експлуатаційного середовища досліджено кінетику електродного потенціалу, вивчено кінетику корозійних процесів у них і визначено швидкості корозії та зменшення товщини стінки труби. Результати досліджень підтверджують дані, отримані з аналізу кінетики потенціалу: найбільша швидкість спостерігається у МС2. найменша – у МС1. Низька швидкість корозії в останньому підтверджує припущення, що швидке зменшення електродного потенціалу у МС1, в основному пов'язане процесами пластичного течіння у сталі трубопроводу, яке неминуче супроводжується утворенням ювенільних поверхонь та субмікротріщин, свіжоутворена поверхня яких має набагато нижчий потенціал. Також найбільшим відносним умістом хлорид-йонів, які перешкоджають її швидкій пасивації. Отримані результати дають змогу коректніше й точніше прогнозувати ресурс та залишковий ресурс промислових трубопроводів з урахуванням впливу механічного та корозійного чинників.*

Ключові слова: *промислові газопроводи, пластові води, внутрішньотрубна корозія, корозійно-механічні випробовування.*

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